MORPHOMETRIC ANALYSIS OF THE ADULT KNEE AND ITS CORRELATION WITH CURRENT KNEE ARTHROPLASTY SYSTEMS

Dissertation submitted for

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Degree Examination

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Chennai, Tamil Nadu

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CERTIFICATE

This is to certify that **“Morphometric analysis of the adult knee and its correlation with current knee arthroplasty systems”** is a bona fide work of **Dr. Samuel Frank Stephen** in partial fulfillment of the requirements for the M.D. Anatomy examination (Branch V) of The Tamil Nadu Dr. M.G.R Medical University to be held in April 2013.

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CONTENTS

ABSTRACT

TITLE: MORPHOMETRIC ANALYSIS OF THE ADULT KNEE AND ITS CORRELATION WITH CURRENT KNEE ARTHROPLASTY SYSTEMS

DEPARTMENT	:	ANATOMY
NAME OF THE CANDIDATE	:	SAMUEL FRANK STEPHEN
DEGREE AND SUBJECT	:	M.D. Anatomy (Branch V)
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OBJECTIVES:

- To measure the dimensions of distal femur, proximal tibia and patella in the Indian population by collecting data from cadaveric knees and dry bones and to obtain the fraction 'Aspect ratio'.
- To compare these dimensions between male and female specimens to identify gender differences.
- To compare the morphometric dimensions with other racial groups and with current knee arthroplasty systems in India

METHODS:

Dissection of the knee joint was done on fourteen adult cadavers (8 female and 6 male) and measured. The dry bones measured were181 femurs and 161 tibias. All the data was entered into Excel workbook sheets (Microsoft Office Excel; version 2007, Microsoft ® Corporation, US.) and analysed using SPSS (version 17.0; SPSS Inc., Chicago, IL). The statistical analyses done were measures of dispersion, bivariate correlation analysis and liner regression analysis. Student's t test for equality of means was performed to determine if the morphological measurements were statistically different between sexes, The Interclass Correlation (ICC) test was used for assessing Rater Reliability.

RESULTS:

- In the dry bones Aspect ratio for the distal femur was 1.29 ± 0.1 and for the proximal tibia was 1.52 ± 0.18.
- In the cadaveric data Aspect ratio for the distal was 1.27 ± 0.4 and for the proximal tibia was 1.48 ± 0.2.
- On comparing the morphometry of the distal femur and proximal tibia between the two genders it was found that the measurements were significantly more in males than in females.
- On comparing with other racial groups the dimensions of the distal femur were smaller as compared to the Caucasian and other Asian races. No such differences were found while comparing the dimensions of the proximal tibia.
- The femoral component of the present knee arthroplasty systems that were considered in this study significantly differed from the distal femoral dimensions obtained whereas the tibial component correlated well with the bone dimensions obtained in this study.

1. INTRODUCTION

Osteoarthritis is a degenerative joint disorder commonly affecting the knees, which is now being treated often by total knee replacement. Success of total knee replacement surgery depends a lot upon the choice of the knee prosthesis. Many studies amongst other population groups have shown the need for a race and gender specific knee prostheses. However, there is scanty literature on the morphometry of the normal adult Indian knee with relevance to knee replacement.

The currently used knee arthroplasty systems for total knee replacement in India are based on morphometric patterns of Western population. There is a need therefore, to improve the design and kinematics of knee prosthesis available in India in order to duplicate patient anatomy more closely. In order to fulfill this need, the initial step would be to have ~~a~~ comprehensive morphometric data on non-osteoarthritic Indian knees.

In this study, dimensions of the distal femur, proximal tibia and patella were measured from dry bones in the Departments of Anatomy at Christian Medical College (CMC) Vellore and St. John's Medical College, Bangalore, and dissected cadavers at CMC Vellore. The male and female knee dimensions were analyzed further to identify significant differences so that the need for gender specificity in knee prosthesis can be ascertained.

The aspect ratio which is the ratio of the medial-lateral dimensions to anterior-posterior dimensions was assessed for the proximal aspect of the tibia and the distal part of the femur in order to determine the individuality of the knee morphometry in the Indian race.

These anthropometric measurements will provide guidelines for designing knee prostheses which are specific for the Indian population.

2. AIM

To study the morphometry of normal adult knees in the Indian population in order to assess the need for a knee arthroplasty system specific to the Indian population.

3. OBJECTIVES

- To measure the dimensions of distal femur, proximal tibia and patella in the Indian population by collecting data from cadaveric knees and categorized dry bones.
- To compare the morphometry of the distal femur, proximal tibia and patella between male and female specimens in order to identify gender differences if any.
- To estimate the mean aspect ratio (mediolateral dimension divided by the anteroposterior dimension) of the femur and tibia in Indian knees.
- To compare the morphometric dimensions with other racial groups across the world.
- To compare the morphometric dimensions with current knee arthroplasty systems in India.

4. LITERATURE REVIEW

4.1: Structure and design of the human knee

The knee is the largest synovial joint in the body and functions to control the centre of body mass and posture in the activities of daily living. This requires a large range of movements in three dimensions together with the ability to withstand high forces.

The joint consists of a complex array of bone, soft tissue, muscle and fluid, making it the most sophisticated joint in the human frame. It has three distinct and partially separated compartments which are; two condyloid joints (tibio-femoral joints), one between each condyle of the femur and the corresponding meniscus and condyle of the tibia; and a third between the patella and the femur (patello-femoral joint), that together form a complex hinge joint. This articulation, allows for motion in six degrees of freedom and makes the knee joint inherently unstable and especially susceptible to damage(1).

4.2: Insult to the knee joint

The knee joint is involved in several degenerative and inflammatory disorders of which the commonest one is osteoarthritis (OA). Osteoarthritis is a chronic degenerative disorder of multi factorial etiology characterized by loss of articular cartilage and periarticular bone remodeling. Studies estimate the prevalence of OA in India is 22-39% (2) amongst patients with joint disease. Osteoarthritis of the knee is the most common cause of locomotor disability in the elderly. Patients with persistent pain and progressive limitation of daily activities despite medical management may be candidates for surgery in whom, total knee replacement is proven to be safe and cost effective treatment for alleviating pain and restoring physical function (2).

4.3: Total knee replacement

The introduction of the total condylar prosthesis by Insall and colleagues in 1972, marks the era of modern knee replacement (3). This prosthesis was the first to replace all three compartments of the knee. Modern total knee arthroplasty consists of resection of the diseased articular surfaces of the knee, followed by resurfacing with metal and polyethylene prosthetic components. For the properly selected patient, the procedure results in significant pain relief, improved function and quality of life (4)

Outcome of a knee replacement surgery may be influenced by factors related to choice of prosthesis. Improvement in success rates have been achieved with the evolution of prosthesis design over time. There are a large number of manufacturers and designs of knee prostheses and currently there is no consensus on prosthesis choice leading to wide variance among individual surgeons (5).

In total knee arthroplasty (TKA), improper fit between the implant and the bony surface leads to several problems. If components are too small (underhang), the bone–implant interface will be reduced leading to higher contact stresses, increased risk of fracture and accelerated process of loosening. The Swedish Knee Arthroplasty Register (2006) reported this problem as the main reason for TKA revision between 1995 and 2004 (6). Conversely, if components are too large (overhang), they may impinge on the surrounding capsular tissues and ligaments, causing pain and limiting the range of motion of the joint(7).

4.4: Anthropometric measurements of the knee joint

Anthropometry is the scientific study of the measurements and proportions of the human body. Various anthropometric measurements of the knee joint have been used to obtain a three dimensional morphometry of the knee joint. The common measurements are anteroposterior and mediolateral dimension of the femur and the tibia. The patellar dimensions measured are mediolateral and superoinferior width.

The aspect ratio of the femur which is the ratio of the mediolateral dimension to the anteroposterior dimension is an important measurement used for correlation and comparison with various knee arthroplasty systems.

A study done by Hitt et al. involved collection of morphometric measurements of the knees of 295 patients undergoing total knee primary arthroplasty. The mean femoral aspect ratio reported for men was 0.81 and for women was 0.84 showing an obvious gender difference, and on correlating the measurements of the distal femoral and proximal tibial measurements with those of existing knee arthroplasty systems, it was found that the prostheses were not adequately sized (8).

In China, Cheng et al. used three dimensional CT measurements of the proximal tibia and distal femur of 172 knees and compared the anthropometric measurements with five total knee prostheses. They found that in the smaller sized prostheses, the tibial mediolateral dimension was undersized while in the larger prostheses there was overhang of the same. Decrease in aspect ratio with increase in anteroposterior diameter was found in both the tibia and the femur, as compared to the constant aspect ratio shown by conventional total knee prostheses(9). These studies show that detailed anthropometric measurements of the knee joint are needed to design better prostheses which may improve the outcome of total knee arthroplasty procedures.

The anthropometric measurements done in studies so far have been performed on osteoarthritic knees either intra-operatively after resection or using computed tomography/ magnetic resonance imaging. However, to ascertain the true measurements and proportions of the human knee, one needs to study normal joints and bones, which is possible only by dissection on cadavers and by dry bone measurements.

4.5: Gender differences in knee morphometry

The major anatomical differences between the knees of males and the knees of females need to be studied to support, or refute the need for a female specific implant design.

Conley et al. have advocated the need for a female-specific total knee design based on three anatomic variations of the female knee as compared to the male knee. These are an increased Q Angle, less prominent anterior medial and lateral femoral condyles and a reduced medial-lateral to antero-posterior (ML:AP) femoral condylar aspect ratio (10). The Q angle is the complimentary angle formed between the patellar tendon and the resultant line of force of the quadriceps muscles. Women have been found to have a larger Q angle than men in several studies (11).

The anterior condylar height is less pronounced in female knees as compared to male knees. Brattstrom et al. conducted a radiological study of the knee anatomy of 200 normal subjects, half of whom were women and found that the anterior height of the lateral and medial condyles in women were 1.5mm and 1.1mm lower as compared to that of the males (12).

The ML: AP aspect ratio has been reported to be less in the female knee. As mentioned earlier, the multi centric study done by (? Kirby) Hitt et al. found that the distal femoral aspect ratio was smaller in females as compared to males and different implants significantly varied in accommodating this difference (12).

There is currently no scientific literature available about the gender differences in knee anthropometric measurements in the Indian population.

4.6: Differences of knee anthropometry between population groups

Anthropometric studies have suggested that current design of total knee arthroplasty (TKA) does not cater to the racial differences in knee anthropometry. Most of the commercially available TKA prostheses are designed according to the anthropometric data of Caucasian knees and this may lead to component mismatch in Asian people.

Yue et al. undertook a study among healthy Chinese and Caucasian subjects, in order to compare their knee anthropometric measurements using three dimensional models of the knees by CT and MRI. The study showed that Chinese females had a significantly narrower distal femur than Caucasian females whereas Chinese men had a wider proximal tibia than their Western counterparts. The study confirmed the hypothesis that there is a significant difference in size and shape between Chinese and Caucasian knees (13).

Ho et al. did morphometric measurements in the resected femurs of seventy Chinese patients who underwent total knee arthroplasty and compared them to five femoral implants currently used. Three implants were found to have a larger medial-lateral width than the total width of the resected distal condyle and so they had a tendency to overhang. The study concluded that femoral implants which were previously shown to be suitable for use in Caucasian patients were not suitable in Chinese patients and manufacturers needed to design femoral implants better suited to Chinese patients (14).

These studies and similar ones done in Japan, Korea and Taiwan show that there are significant racial differences in the shape and size of the knee and this may impact on the design of implants used in total knee arthroplasty.

4.7: Anthropometric measurements of the knee joint in the Indian population

In India, a morphometric study was done by Vaidya et al. among patients with osteoarthritis using CT scan. 47 patients with osteoarthritis were studied of which 21 were men and 26 women. The study showed that most Indian men (86.8%) could have the femoral component satisfactorily replaced by available designs. However, a statistically significant number of women (60.4%) had femoral anteroposterior diameters smaller than the smallest available femoral component and they also had splaying in mediolateral dimension. This study concluded that the implants currently used for TKA in India were not suitable for the knee morphology of Indian patients (15).

Bagaria et al. conducted a study to measure the dimensions of knee joints among Indians using MRI scans of 25 patients who underwent bilateral knee scans for various joint pathologies. The mediolateral, anteroposterior dimensions and the aspect ratio of the femur, tibia and patella were measured and compared with the prostheses. The study concluded that none of the current prostheses designs correlated well with the patient's measurements. (16).

In India, there is scanty literature available on the anthropometric measurements of the knee joint for the purpose of correlating with the knee prostheses currently being used here. Furthermore, the studies done so far have been imaging studies which may not provide accurate measurements needed for designing prosthesis.

5. MATERIALS AND METHODS

The study was done after approval from the Institutional Review Board (IRB) and Ethics Committee. The study included measurements on knees of adult cadavers and unpaired dry adult bones.

Dissection of the knee joint was done on fourteen adult cadavers (8 female and 6 male) during routine dissection in the Department of Anatomy, Christian Medical College Vellore. All cadavers were embalmed and stored in 5% formalin solution. The knee joint was meticulously dissected using standard instruments and the distal femur, proximal tibia and patella were completely exposed for measurements.

The dry bones (181 femurs and 161 tibias) were obtained both from the Department of Anatomy, St. John's Medical College, Bangalore as well as the Department of Anatomy, Christian Medical College, Vellore. Bones having deformity, fractures, unfused epiphyses and macerated condyles were not included in the study.

Measurements (in cadavers and bones) were taken using the Sliding Digital Caliper (ROBUST, Germany), with a resolution of 0.01mm (Figure **1a**).

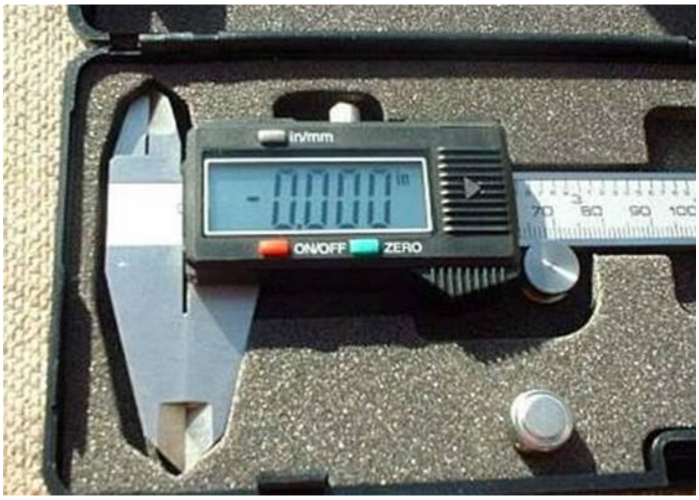

Figure **1a**: Sliding digital caliper

Figure **1b**: Field Osteometric Board

Figure **1c**: Tailor’s inch tape

Bone length was measured using sliding Field Osteometric Board (0-90cm) (Figure **1b**).

Cadaver height was measured using a tailor's inch tape (0-150cm), resolution of 1.0mm (Figure **1c**).

A sufficient period of 'trial and error' (pilot study) preceded actual systematic record of measurements. Parameters of the knee were standardized and measured to 1/100th of a millimeter. Each measurement was made by one observer, voiced vocally and recorded on a Dictaphone and its repeat measurement was done on another day in the same way to reduce intra-observer bias that might arise. The readings were then entered in the data form after all the measurements had been done (Annexure I, II).

The parameters included were:

5.1: Condylar measurements in Distal Femur

5.1.1: Medio-lateral length (ML): This dimension was defined as the maximum distance between the two femoral condyles at the transepicondylar axis (Figure **2a**).

5.1.2: Antero-posterior length (AP): The anteroposterior length of the medial (APMC) and lateral condyle (APLC) was measured

Figure **2a**: Measurement of Medio-lateral length (ML) between epicondyles at the distal end of the right femur

Figure **2b:** Measurement of Antero-posterior length (AP) of the medial condyle at the distal end of the right femur

Figure **2c:** Measurement of Width (W) of the medial condyle at the transepicondylar plane of the right femur separately and was defined as the largest measurement along its length (Figure **2b**).

5.1.3: Width of condyles (W): This dimension was defined as the maximum thickness of the medial (WMC) and lateral (WLC) condyle at the transepicondylar plane (Figure **2c**).

5.1.4: Height of condyles (H): This dimension was defined as the maximum distance from the tangent drawn to each condyle (parallel to the transepicondylar axis) to the superior aspect of the of the articular surface of the medial (HMC) and lateral (HLC) condyle (Figure **2d**).

5.1.5: Depth of intercondylar notch (DIC): This dimension was defined as the antero-posterior depth of the femoral intercondylar notch at the transepicondylar plane (Figure **2e**).

5.1.6: Width of intercondylar notch (WIC): This dimension was defined as the maximum width of the femoral intercondylar notch (Figure **2f**).

5.1.7: Femoral length: Length of the femur was measured using the sliding osteometric board and defined as the maximum measurement from the head of the femur to the common horizontal tangent to both condyles (Figure **1b**).

Figure **2d**: Measurement of Height (H) of the medial condyle at the distal end of the right femur


Figure **2e:** Measurement of Depth of intercondylar notch (DIC) at the distal end of the right femur

Figure **2f:** Measurement of Width of intercondylar notch (WIC) at the distal end of the right femur

5.2: Articular surface measurements in Distal Femur

5.2.1: First horizontal dimension on anterior articular surface (A): This dimension was the distance between the medial margin to the lateral margin of the femoral anterior articular surface at a level just inferior to the patellar extension on the lateral condyle (Figure **3a**).

5.2.2: Second horizontal dimension on anterior articular surface (B): This dimension was defined as the extent between the medial margin to the lateral margin of the femoral anterior articular surface at the anterior limit of the intercondylar notch (Figure **3b**).

5.2.3: Width of condyles: These dimensions were defined as the width of the articular surface of medial (CM) and lateral (CL) condyles along the transepicondylar plane (Figure **3c**).

5.2.4: Patellar extension on the lateral condyle (X): This dimension was defined as the extent to which the lateral condylar femoral articular surface exceeding that of the medial condyle (Figure **3d**).

5.2.5: Anteroposterior extent of anterior femoral articular surface (Y): This dimension was defined as the midline anteroposterior distance of distal femoral articular surface (Figure **3e**).

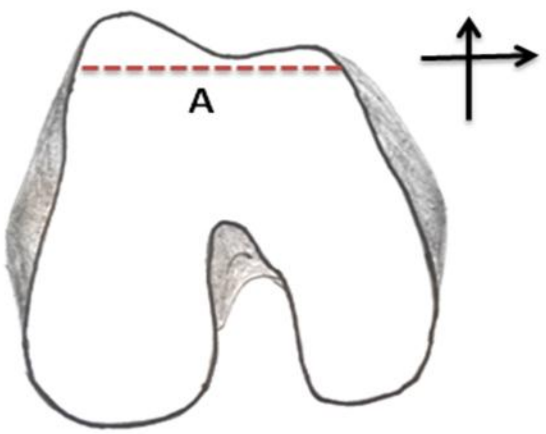

Figure **3a:** Measurement of the first horizontal dimension (A) of the articular surface of the distal end of the right femur.

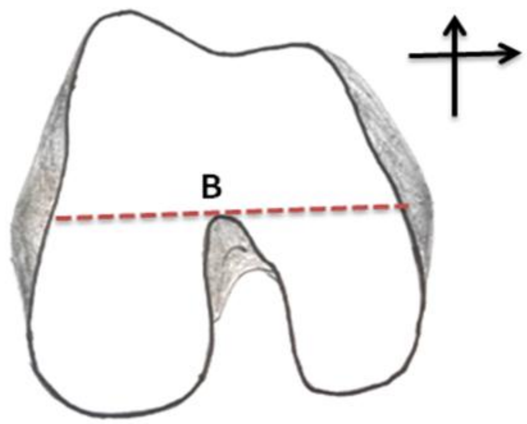

Figure **3b:** Measurement of the second horizontal dimension (B) of the articular surface of the distal end of the right femur.

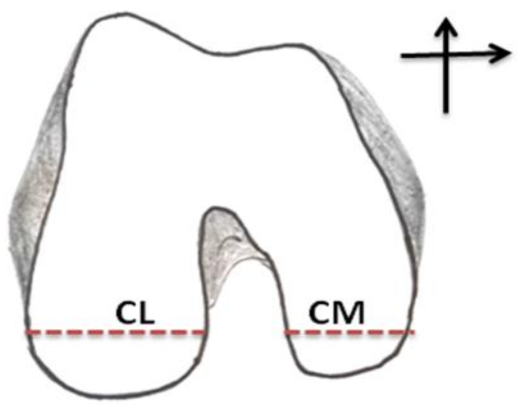

Figure **3c:** Measurement of the width of the condyles (CM, CL) of the articular surface of the distal end of the right femur

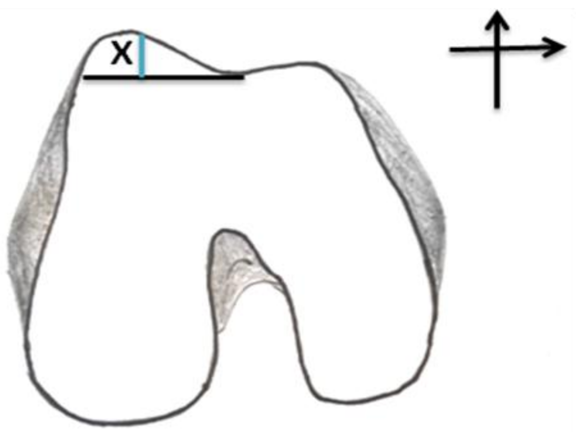

Figure **3d:** Measurement of the patellar extension of the lateral condylar articular surface (X) of the distal end of the right femur

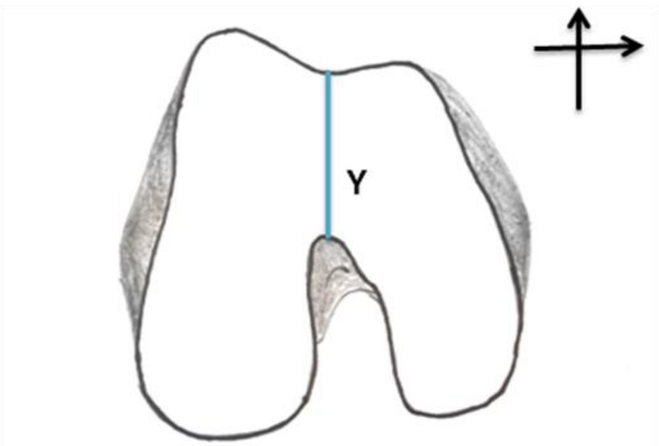

Figure **3e:** Measurement of the anteroposterior extent of intercondylar femoral articular surface (Y) of the distal end of the right femur

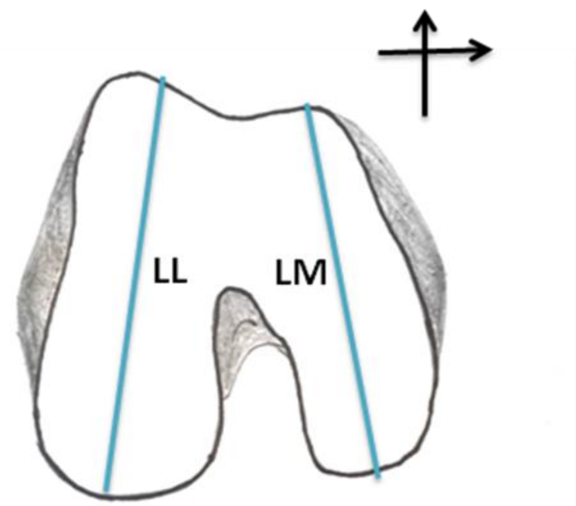

Figure **3f:** Measurement of the length (LM. LL) of the articular surface of the distal end of the right femur

5.2.6: Length of articular surface of femoral condyles: The length of the articular surface of the medial (LM) and lateral (LL) condyles was measured along the middle of the articular surface using an inch tape (0-150cm) (Figure **3f**).

5.3: Condylar measurements in Proximal tibia

5.3.1: Anteroposterior length (AP): The maximum anteroposterior length of the medial (APMC) and lateral (APLC) tibial condyle was measured separately. The midline anteroposterior length (MAP) was defined as the anteroposterior distance in the intercondylar region opposite the tibial tuberosity (Figure **4a**).

5.3.2: Mediolateral length (ML): This was defined as the maximum length in the mediolateral dimension (Figure **4b**).

5.4: Articular surface measurements in Proximal tibia

5.4.1: Mediolateral dimension of the tibial articular surface: This dimension was measured on both medial (L) and lateral (K) condyles as the maximum horizontal distance from the corresponding intercondylar tubercle to the articular margin (Figure **4c**).

Figure **4a:** Measurement of the midline anteroposterior length (MAP) of the proximal end of the right tibia.

Figure **4b:** Measurement of the mediolateral length (ML) of the proximal end of the right tibia.

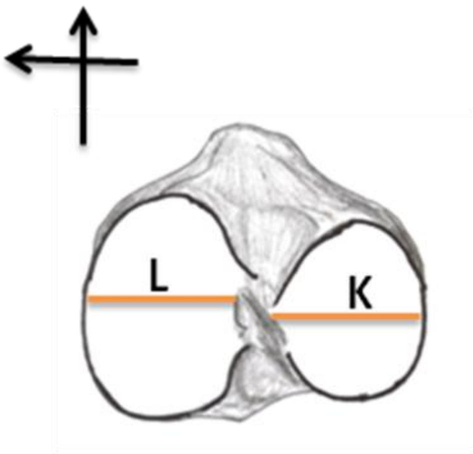

Figure **4c:** Measurement of the mediolateral length (L, K) of the right tibial articular surface.

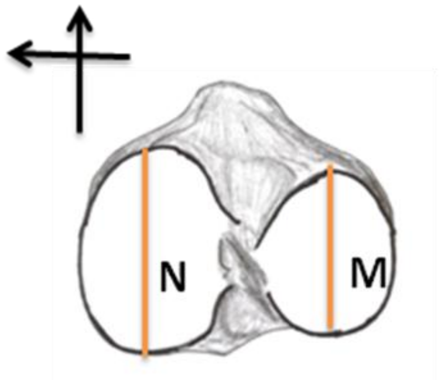

Figure **4d:** Measurement of the anteroposterior length (N, M) of the right tibial articular surface.

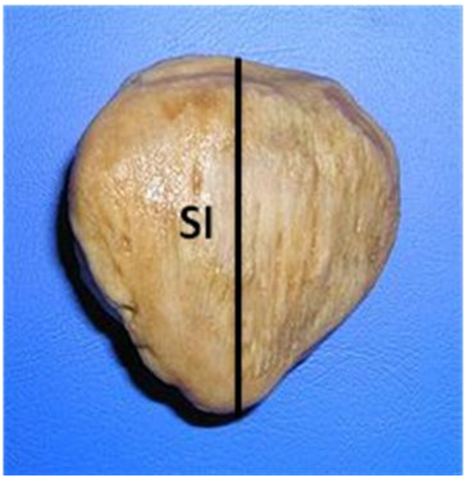

Figure **5a:** Measurement of the superoinferior length (SI) of the right patella.

5.4.2: Anteroposterior dimension of the tibial articular surface: This dimension was measured on both medial (N) and lateral (M) condyles as the maximum anteroposterior distance between the tangents on the anterior and posterior borders of the respective articular surfaces (Figure **4d**).

5.5: Measurements of Patella

5.5.1: Superoinferior length (SI): This dimension was defined as the maximum vertical distance from the base to the apex of the patella (Figure **5a**).

5.5.2: Mediolateral length (ML): This dimension was defined as the maximum horizontal distance between the two borders of the patella (Figure **5b**).

5.5.3: Thickness (T): This dimension was defined as the maximum thickness of the patella from the anterior surface to the vertical intra-articular ridge on the posterior surface of the patella

5.6: Patellar Articular Surface Measurements

5.6.1: Articular Superoinferior length (aSI): This dimension was defined as the maximum vertical length between the margins of the articular surface on the posterior surface of the patella (Figure **5c**).

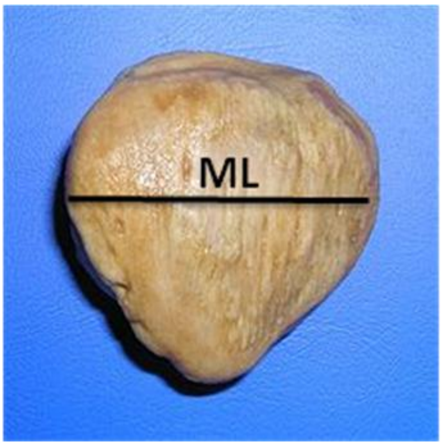

Figure **5b:** Measurement of the mediolateral length (ML) of the right patella.

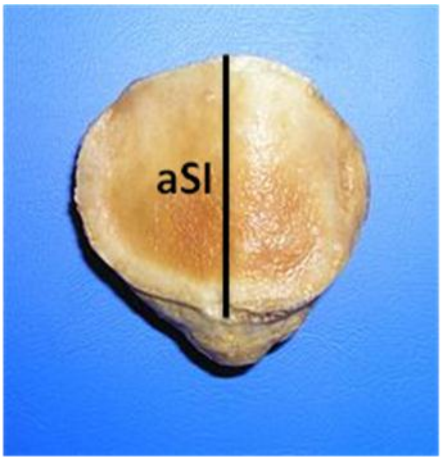

Figure **5c:** Measurement of the superoinferior length (aSI) of the articular surface of the right patella.

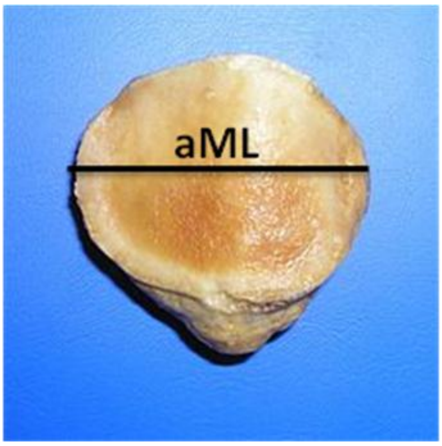

Figure **5d:** Measurement of the mediolateral length (aML) of the articular surface of the right patella.

5.6.2: Articular Mediolateral length (aML): This dimension was defined as the maximum horizontal length between the margins of the articular surface on the posterior surface of the patella (Figure **5d**).

5.7: Analysis

All the data was entered into Excel workbook sheets (Microsoft Office Excel; version 2007, Microsoft ® Corporation, US.) and analysed using SPSS (version 17.0; SPSS Inc., Chicago, IL).

The data was analysed as follows.

The dimensions were summarized as the *mean* and *standard deviation* and compared using *paired t-test.*

5.7.1: Aspect Ratio (AR): The aspect ratio (which is calculated as the mediolateral dimension divided by the anteroposterior dimension) was noted using various dimensions of the femur and the tibia.

For Femur:

AR 1= ML/ APMC

AR 2= ML/ APAVG, [APAVG = average of the anteroposterior distance of medial (APMC) and lateral (APLC) condyle]

For Tibia:

AR 1= ML/ APMC

AR 2= ML/ MAP

AR 3= ML/ APAVG, [APAVG = average of the anteroposterior distance of medial (APMC) and lateral (APLC) condyle]

The ANOVA (analysis of variance) was applied to find out the statistical difference between the means of different types of Aspect ratios.

5.7.2: Reliability (Data reliability): The *Interclass Correlation* (ICC) test was used for assessing Rater Reliability.

5.7.3: Correlation:

Bivariate correlation was done between various sets of variables and the Pearson's correlation coefficient obtained was interpreted to identify positive linear, low positive, negative or no correlation. A Pearson's coefficient close to +1 is said to have high positive correlation between the variables. A Pearson's coefficient close to -1 is said to have strong negative correlation between the variables. Other values of the coefficient can be interpreted as a gradient between +1 to 0 to -1. All values of the Pearson's coefficient should be accompanied with a statistically significant p value (*p value* of < 0.05 was taken as significant).

Scatter plots with best-fit lines were calculated with the use of *least-squares regression* to graphically visualize the correlation between two variables; where the slope of the graph is $(r)^2$, where "r" is the Pearson's correlation coefficient.

In a scenario if variables are said to have a high positive correlation, then **linear regression** between them can be calculated to arrive at a regression equation which helps to determine the dependent variable from the independent variable as below:

Independent variable = 'B constant' + factor x dependent variable.

Linear Regression was done for variables which were independent of each other (i.e.: not derived from each other) and were not belonging to a mixed sample.

A *Student's t test for equality of means* was performed to determine if the morphological measurements were statistically different between sexes (in cadaveric data) and two sides of unpaired bones. All statistical tests were two-tailed and a *p value* of < 0.05 was taken as significant.

The 'Aspect Ratio' was compared with data from other studies involving different racial groups and also with prosthetic systems (Depuy, Altius) currently used by the Department of Orthopedics, Christian Medical College, Vellore.

5.8: Conflict of interest

There were no benefits or funds received from companies in support of the study and no personal relationships with organizations that could inappropriately influence or bias this work.

6. RESULTS

6.1: RESULTS OF THE BONE MORPHOMETRIC MEASUREMENTS (FEMUR)

Morphometric measurements were done for 177 unpaired femurs in dry bones; out of which 92 were right sided and 85 were left sided. The mean aspect ratio of the femurs was found to be 1.29 (± 0.1). The measurements of the femurs are summarized in Table 1.

Morphometric Measurement	**Mean (mm)**	**Median (mm)**	**Standard Deviation**	**Range**	
				Minimum (mm)	**Maximum (mm)**
Length	436.83	435.0	27.161	378	500
APMC	58.15	58.2	3.64	50.7	68.5
APLC	57.58	57.6	3.34	50.8	70.0
ML	74.96	75.2	4.08	65.3	84.1
Aspect Ratio (ML/ APMC)	1.29	1.29	0.05	1.12	1.44

APMC- Anteroposterior length of medial condyle; APLC- anteroposterior length of lateral condyle; ML- Mediolateral length at transepicondylar axis

TABLE 1: Measures of dispersion for dimensions of distal femur (dry bones) (N=177)

6.1.1: Comparison of Right and Left femoral dimension

On comparison of the right and left femurs in dry bones it was found that the mean APMC and Aspect ratio were significantly different between right and left femurs. The mean APMC of the right side was 57.56 and that of the left side was 58.78, the difference of the APMC was 1.22 mm (left more than right, *p value* 0.02). The mean Aspect ratio of the right side was 1.30 and that of the left side was 1.28, (right more than left, *p value* 0.02). There was no statistical difference between means of Length, APLC or ML; results as shown in Table 2.

Morphometric Measurement	**Right femur Mean (mm)**	**Left femur Mean (mm)**	**Standard Error of difference between means**	**p value**
Length	433.07	441.30	6.1	0.20
APMC	57.56	58.78	0.54	0.02
APLC	57.75	57.39	0.50	0.48
ML	74.76	75.18	0.61	0.5
Aspect Ratio	1.30	1.28	0.00	0.02

APMC- Anteroposterior length of medial condyle; APLC- Anteroposterior length of lateral condyle; ML- Mediolateral length at transepicondylar axis

TABLE 2: Comparison of means of femoral dimensions between sides

6.1.2: Difference in methods of calculating Aspect ratio of femur

In this study the Aspect ratio of femur was calculated in two ways. The first method (Aspect ratio 1) was calculated as the ratio of ML and APMC and the second method (Aspect ratio 2) being the ratio of ML and the average of APMC and APLC (APAVG). The means of both Aspect ratio 1 and Aspect ratio 2 was 1.29. There was significant positive correlation (*Pearson's r value* = 0.90, *p value* 0.00) between Aspect ratio 1 and Aspect ratio 2 as shown in Figure **6**.

6.1.3: Correlation between femur dimensions

Correlation analysis was done between various femoral dimensions measured for 177 femurs. There was positive correlation between APMC and the ML dimensions of the femur, i.e. as the anteroposterior dimensions of the distal femur increased there was a linear proportionate increase in the mediolateral width. The Aspect ratio 1 correlated moderately with APMC (negative correlation). However ML and APAVG did not show any correlation with the Aspect ratio 1 (Table 3)

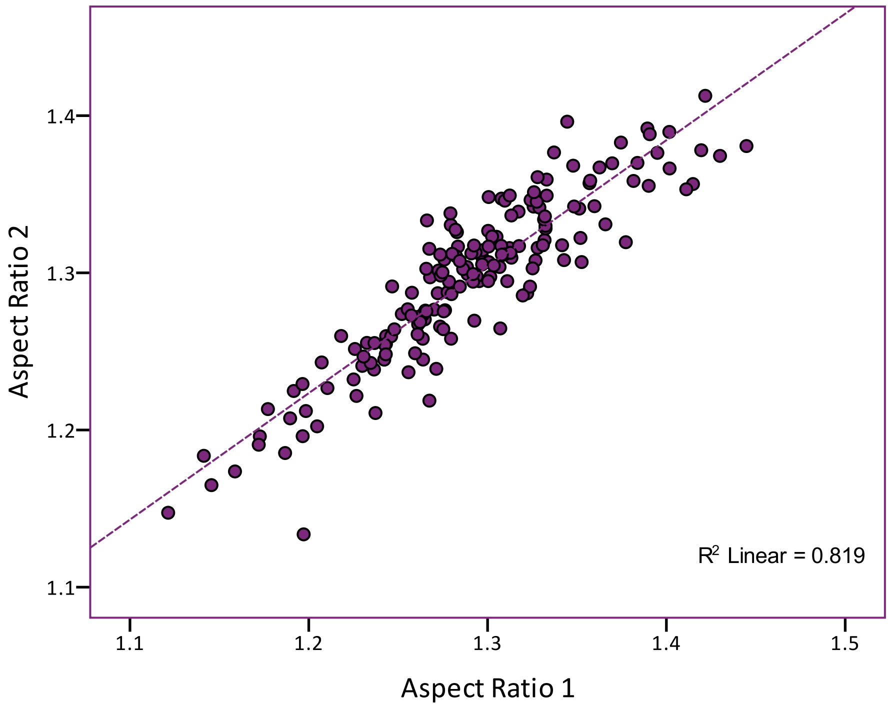

Figure **6:** Correlation between Aspect Ratio 1 and Aspect ratio 2 (N = 177), showing a linear positive correlation. Pearson's r value = 0.90

S.No.	X- Axis	Y- Axis	Pearson's r value	p value
1	APMC	ML	0.70	0.00
2	APMC	AR 1	-0.52	0.00
3	ML	AR 1	0.23	0.02
4	APAVG	AR 1	-0.42	0.00

APMC- Anteroposterior length of medial condyle; APAVG- Average of Anteroposterior length of medial and lateral condyle; ML- Mediolateral length at transepicondylar axis; AR 1- Aspect ratio 1(ML/APMC)

Table 3: Correlation between various femoral dimensions.

The correlation scatter plots for the dimensions in Table 3 are shown in Figures 7, 8, 9 and 10.

6.1.4: Correlation between femoral length and other femoral dimensions

The length of the femur was found to have low to moderate correlation with APMC (*Pearson's r* = 0.61) and ML (*Pearson's r* = 0.58) and no correlation with Aspect ratio 1 (Table 4), proving the incapability of predicting APMC, ML or Aspect ratio using the length of the femur.

S.No.	**X- Axis**	**Y- Axis**	**Pearson's r value**	**p value**
1	Length of femur	APMC	0.61	0.00
2	Length of femur	ML	0.58	0.00
3	Length of femur	AR 1	-0.026	0.82

APMC- Anteroposterior length of medial condyle; ML- Mediolateral length at transepicondylar axis; AR 1- Aspect ratio 1(ML/APMC)

Table 4: Correlation of Length of femur with other femoral dimensions

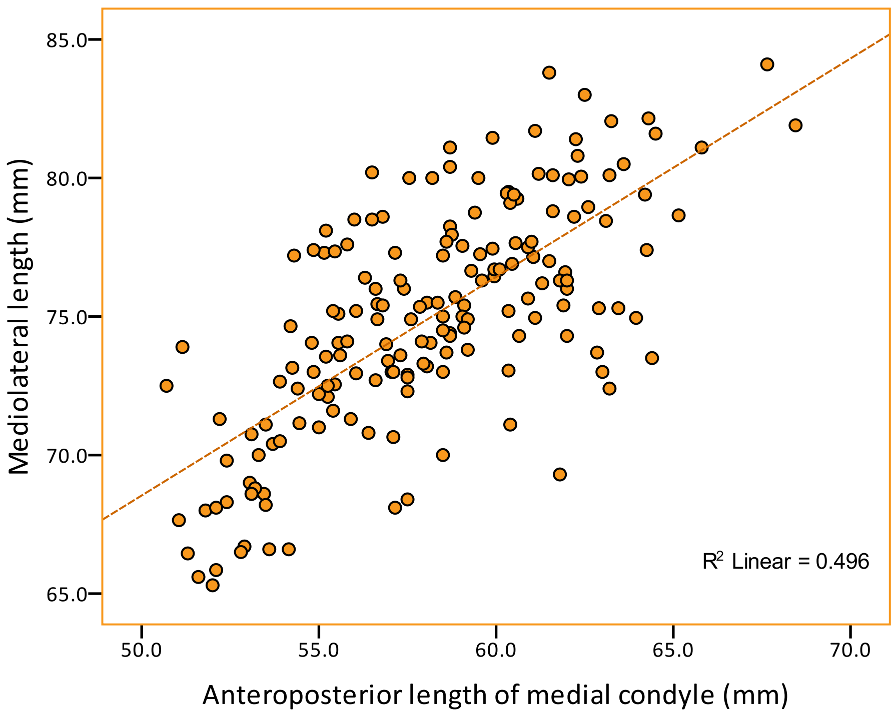

Figure 7: Correlation between APMC and ML of femur (N = 177) showing a linear positive correlation. Pearson's r = 0.70.

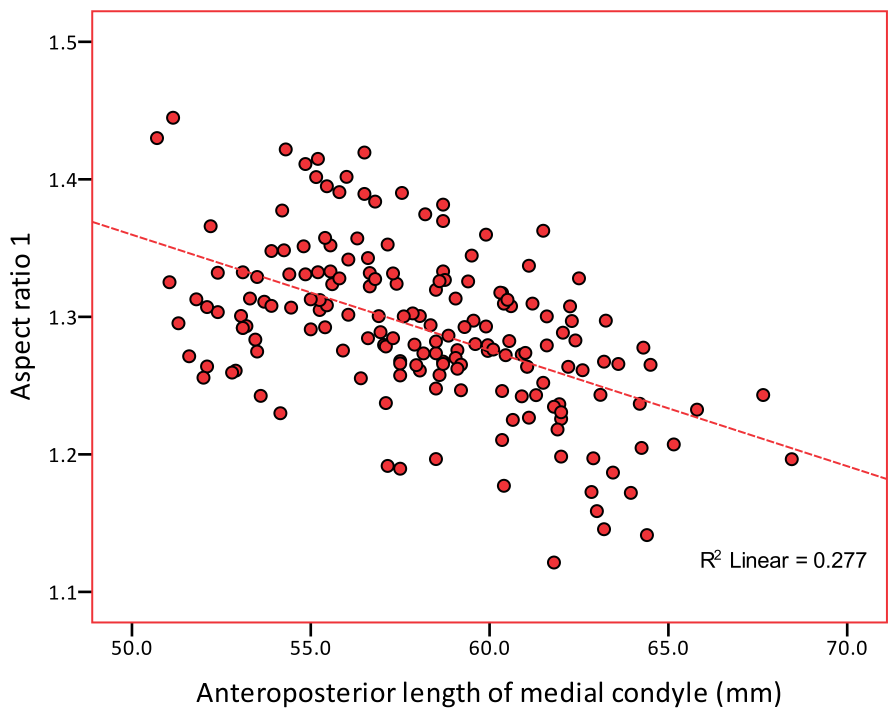

Figure 8: Correlation between APMC and Aspect ratio 1 of femur (N = 177) showing a negative correlation. Pearson's r = -0.52.

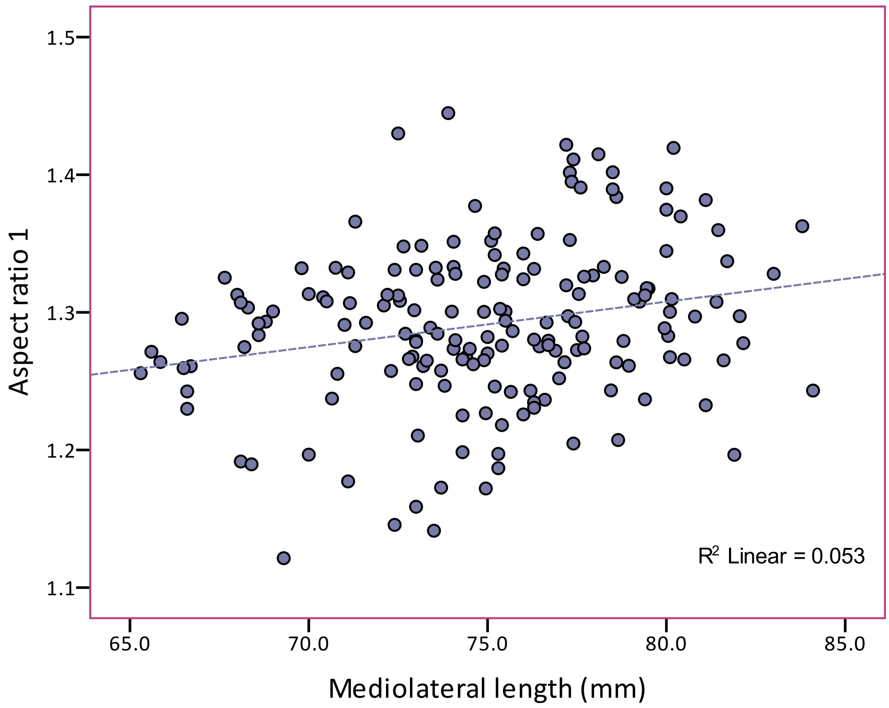

Figure 9: Correlation between ML and Aspect ratio 1 of femur (N = 177) showing low correlation. Pearson's r = 0.23.

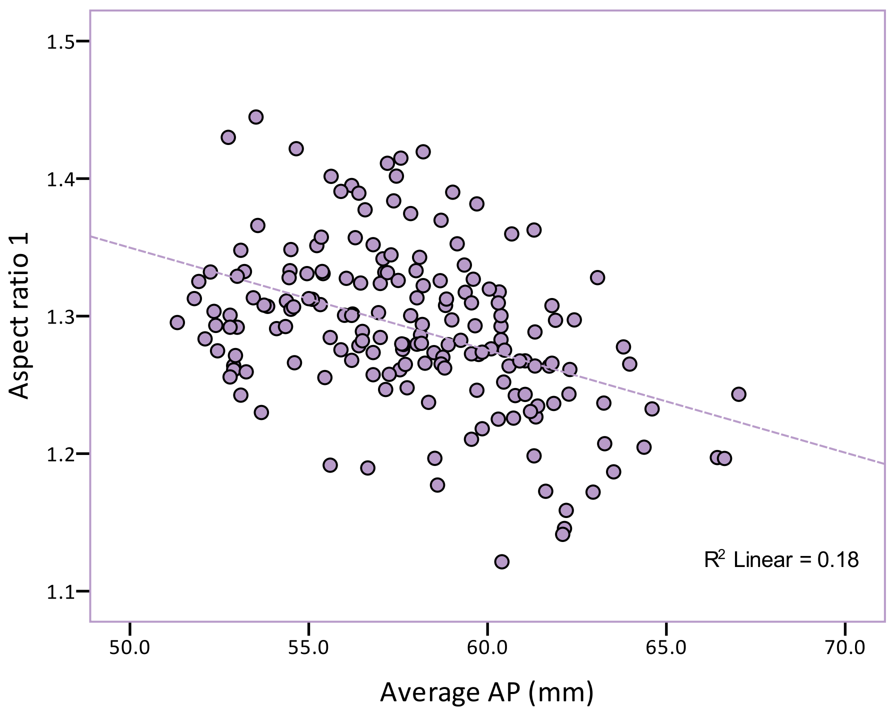

Figure 10: Correlation between Average AP and Aspect ratio 1 of femur (N = 177) showing negative correlation. Pearson's r = -0.42

The correlation scatter plots between Length of femur and other femoral dimensions are shown in Figures 11, 12 and 13.

6.1.5: Regression analysis in femur

As can be gathered from the scatter plot (Figure 7) the best parameter to predict the mediolateral width of distal femur is APMC since, the relationship between APMC and ML appears to be straight (positive linear correlation, *r= 0.70, p value 0.00*) and there is no evidence of a mixed sample. The variables are independent and no obvious outliers are visible. Therefore for the 177 femurs using APMC as independent variable and ML as the dependent variable, the linear regression equation thus obtained is:

The Regression equation for femur is: ML = 29.11 + 0.78 (APMC)

For example: For given APMC = 53.0 mm using the regression equation,

ML = 29.11 + 0.78 (53.0)

ML = 70.45 mm

Linear regression analysis could not be done for other variables since they were not independent of each other, though they were not belonging to a mixed sample and showed correlation.

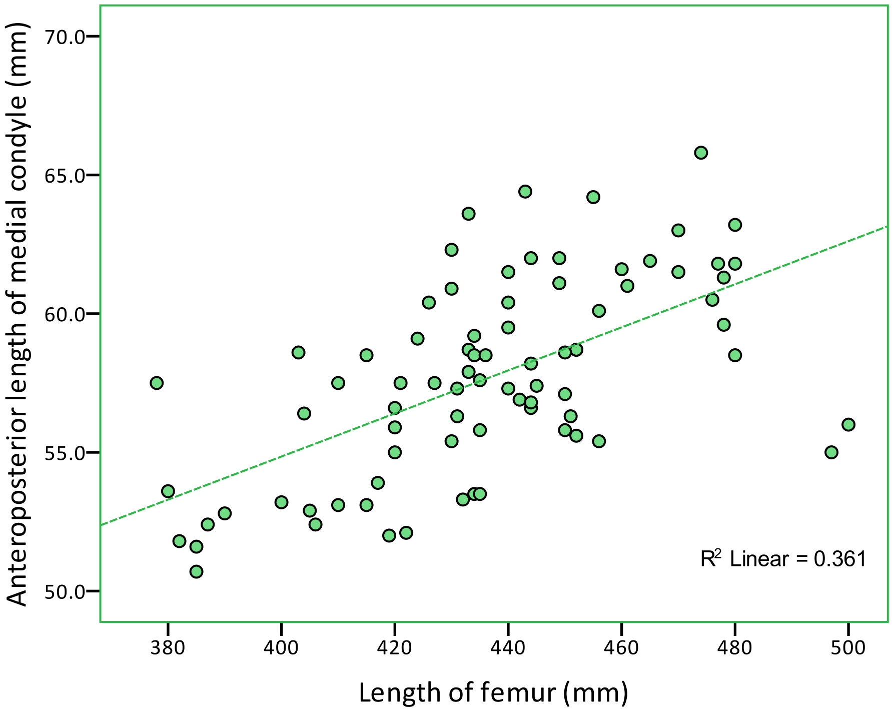

Figure 11: Correlation between Length of femur and APMC of femur (N = 81) showing moderate correlation. Pearson's r = 0.61.

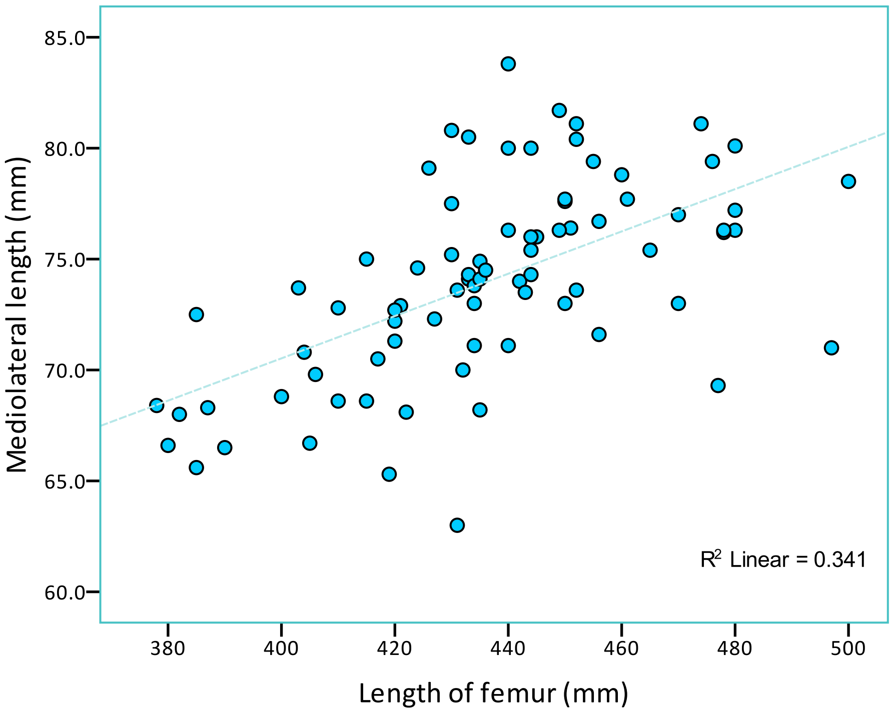

Figure 12: Correlation between Length of femur and ML of femur (N = 81) showing low to moderate correlation. Pearson's r = 0.58.

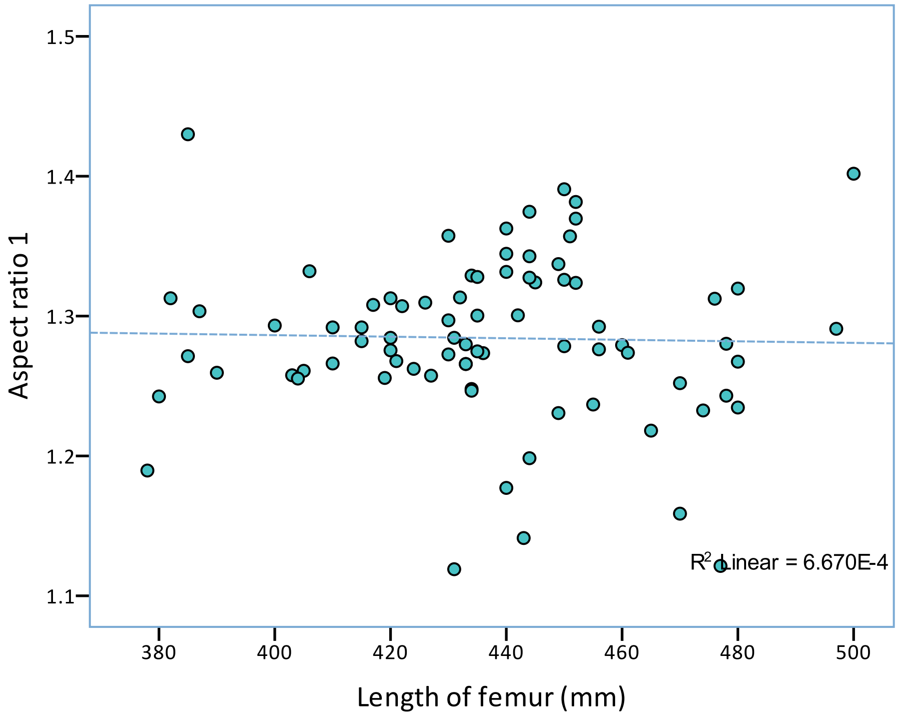

Figure 13: Correlation between Length of femur and Aspect ratio 1 of femur (N = 81) showing no correlation.

6.2 RESULTS OF THE BONE MORPHOMETRIC MEASUREMENTS (TIBIA)

Morphometric measurements were done for 161 unpaired adult tibias (dry bones); out of which 84 were right sided and 77 were left sided. The mean aspect ratio of the tibia bones was found to be 1.15 (± 0.56). The measurements of the tibias are summarized in Table 5.

Morphometric Measurement	**Mean (mm)**	**Median (mm)**	**Standard Deviation**	**Range**	
				Minimum (mm)	**Maximum (mm)**
Length	368.74	370.0	20.11	322	410
APMC	45.12	44.6	4.05	36.0	56.5
APLC	39.96	39.4	3.25	31.7	52.3
MAP	48.10	47.7	4.77	37.5	60.6
ML	68.4	68.3	4.87	55.6	80.9
Aspect Ratio 1 = ML/ APMC	1.52	1.52	0.09	1.27	1.82

APMC- Anteroposterior length of medial condyle; APLC- Anteroposterior length of lateral condyle; MAP- Midline anteroposterior length; ML- Maximum mediolateral length

TABLE 5: Measures of dispersion for tibias (for dry bones); (N=161)

6.2.1: Comparison of Right and Left tibial dimension

On comparison of the right and left tibias in dry bones it was found that there was no significantly difference between the means of any dimension as shown in Table 6.

Morphometric Measurement	**Right tibia Mean (mm)**	**Left tibia Mean (mm)**	**Standard Error of difference between means**	**p value**
Length	374.92	362.04	5.44	0.32
APMC	45.35	44.88	0.64	0.46
APLC	40.16	39.73	0.51	0.40
MAP	48.67	47.48	0.75	0.11
ML	68.84	67.95	0.76	0.24
Aspect Ratio 1 = ML/ APMC	1.52	1.51	0.01	0.77

APMC- Anteroposterior length of medial condyle; APLC- Anteroposterior length of lateral condyle; MAP- Midline anteroposterior length; ML- Maximum mediolateral length

TABLE 6: Comparison of means of tibial dimensions between sides

6.2.2: Difference in methods of calculating Aspect ratio of tibia

In this study the Aspect ratio of tibia was calculated in three ways. The first method (Aspect ratio 1) was calculated as the ratio of ML and APMC, the second method (Aspect ratio 2) was calculated as the ratio of ML and the midline anteroposterior length (MAP) and the third being the ratio of ML and the average of APMC, APLC and MAP (APAVG). However with the application of the ANOVA test; this study shows that there is no statistically significant difference between the means of Aspect Ratio 1, 2 or 3 as shown in Table 7.

Aspect Ratio	**Mean**	**F statistic** (between groups)	**p value**
Aspect ratio 1	1.52	0.084	0.77
Aspect ratio 2	1.42	0.843	0.36
Aspect ratio 3	1.54	0.015	0.90

Aspect ratio 1 = ML/ APMC, Aspect ratio 2 = ML/ MAP, Aspect ratio 3 = ML/ Average of APMC, APLC and MAP

TABLE 7: Analysis of Variance (ANOVA) for the Aspect ratios 1, 2, 3 of tibia

The correlation scatter overlay plot between the Aspect ratios for tibia was computed (Figure **14**) and found that there is significant correlation between them as shown in Table 8.

S.No.	X- Axis	Y- Axis	Pearson's r value	p value
1	Aspect ratio 1	Aspect ratio 2	0.47	0.00
2	Aspect ratio 1	Aspect ratio 3	0.81	0.00
3	Aspect ratio 2	Aspect ratio 3	0.81	0.00

Aspect ratio 1 = ML/ APMC, Aspect ratio 2 = ML/ MAP, Aspect ratio 3 = ML/ Average of APMC, APLC and MAP

Table 8: Correlation of Aspect ratios of tibial dimensions

Since there is no significant difference between the aspect ratios 1, 2, 3 (*p value* 0.00); Aspect ratio 1 has been used for further analysis of tibia.

6.2.3: Correlation between other tibial dimensions

For the 161 tibias in this study correlation analysis was done between the various dimensions (Table 9). There was positive correlation between APMC and ML (*Pearson's r* = 0.753, *p value 0.00*) and between MAP and ML (*Pearson's r* = 0.754, *p value 0.00*)

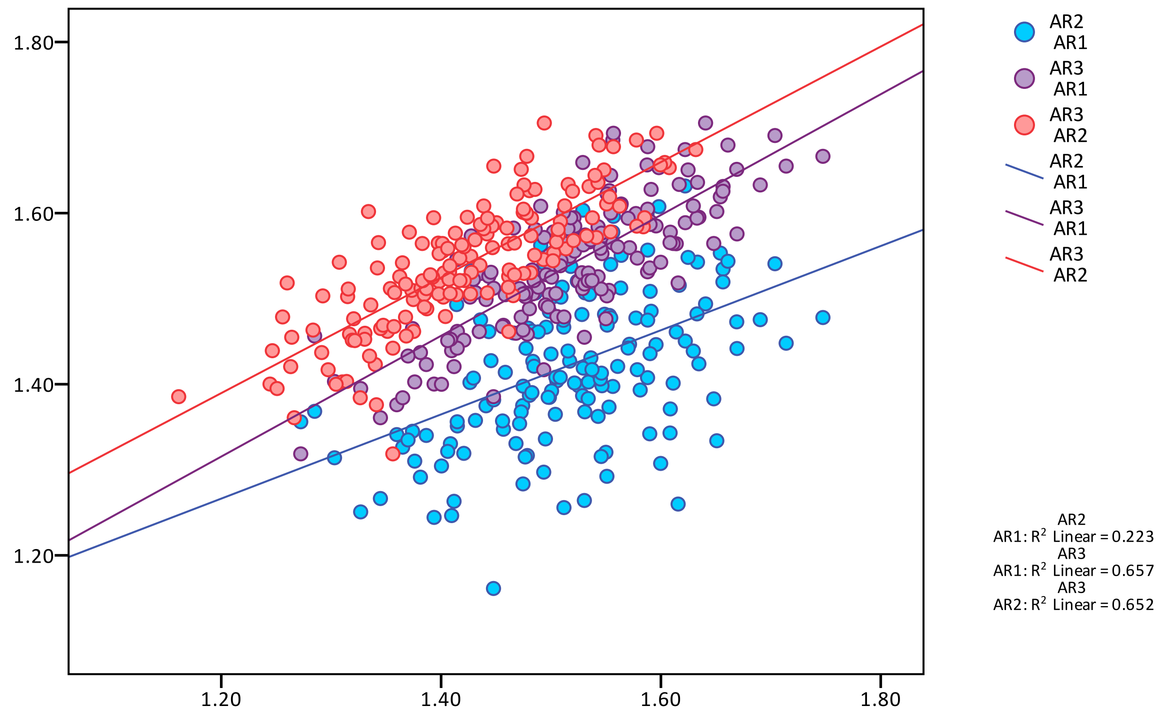

Figure 14: Correlation scatter overlay between tibial Aspect ratios 1, 2 and 3 (N = 161)

i.e. as the anteroposterior length (of the medial condyle and the midline AP) of the proximal tibia increased, there was a proportionate increase in the mediolateral width linearly as shown in Figures **15, 16**. There was however no correlation between the other dimensions (Figures **17, 18 and 19**).

S.No.	X- Axis	Y- Axis	Pearson's r value	p value
1	APMC	ML	0.753	0.00
2	MAP	ML	0.754	0.00
3	APMC	AR 1	-0.57	0.00
4	ML	AR 1	0.10	0.19
5	MAP	AR 1	-0.23	0.00

APMC- Anteroposterior length of medial condyle; APLC- Anteroposterior length of lateral condyle; MAP- Midline anteroposterior length; ML- Maximum mediolateral length; Aspect ratio 1 = ML/ APMC

Table 9: Correlation between various tibial dimensions

The other variables show no correlation between them as shown in Figures 17, 18 and 19.

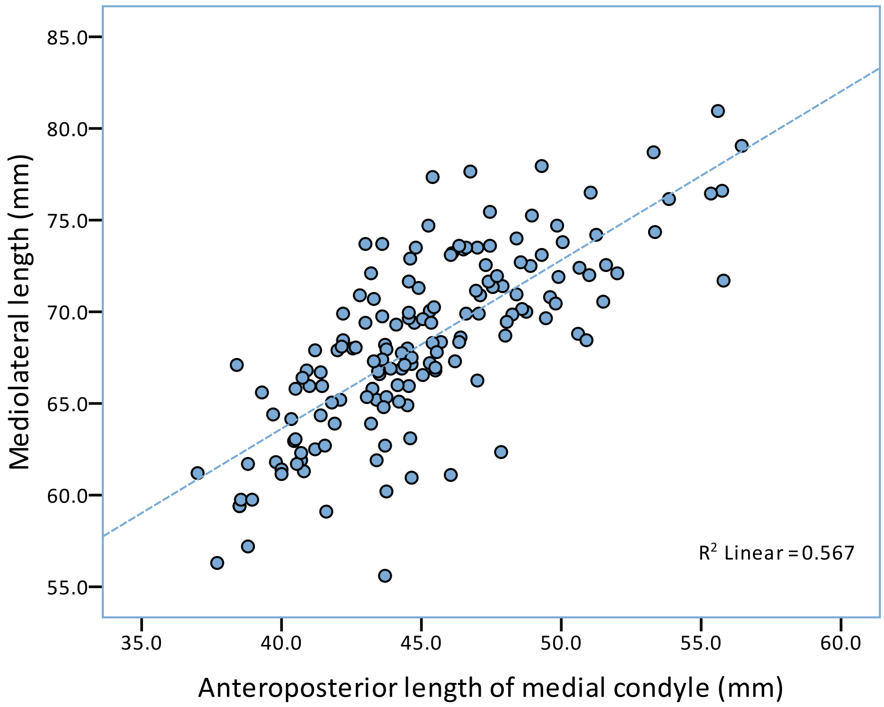

Figure 15: Correlation between APMC and ML of tibia (N = 161) showing strong positive correlation between APMC and ML of the proximal tibia. Pearson's r = 0.75.

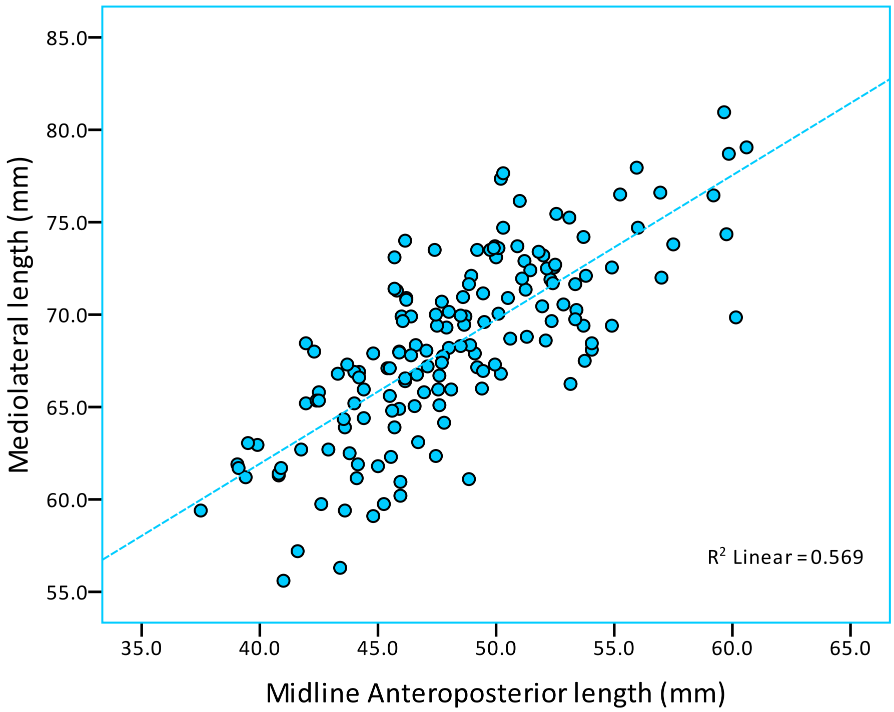

Figure 16: Correlation between MAP and ML of tibia (N = 161) showing strong correlation between the two variables. Pearson's r = 0.75.

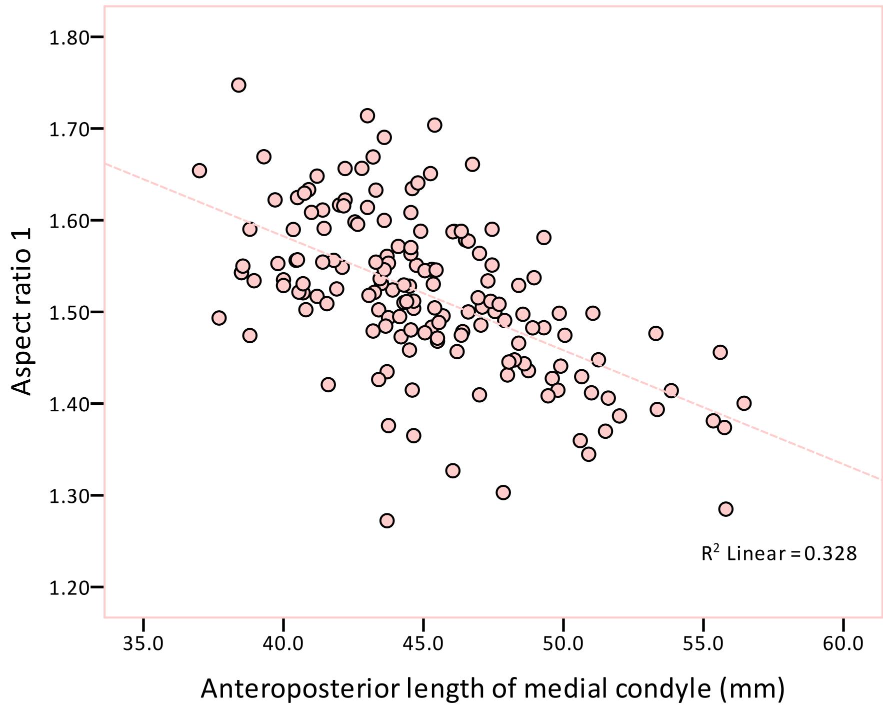

Figure 17: Correlation between APMC and Aspect ratio 1 of tibia (N = 161), showing negative correlation. Pearson's r = -0.57.

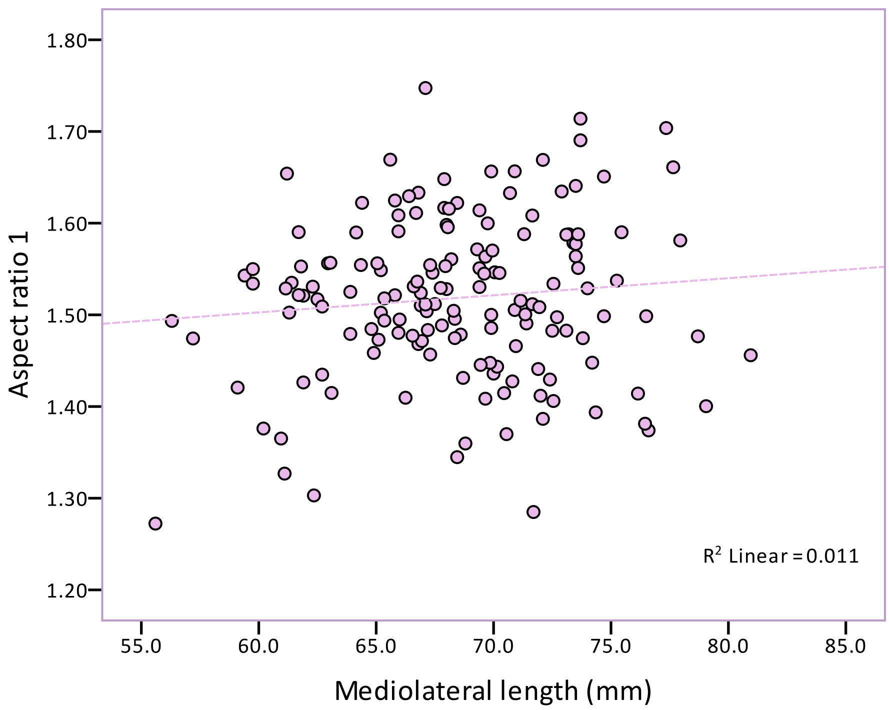

Figure 18: Correlation between ML and Aspect ratio 1 of tibia (N = 161), showing low correlation. Pearson's r = 0.10.

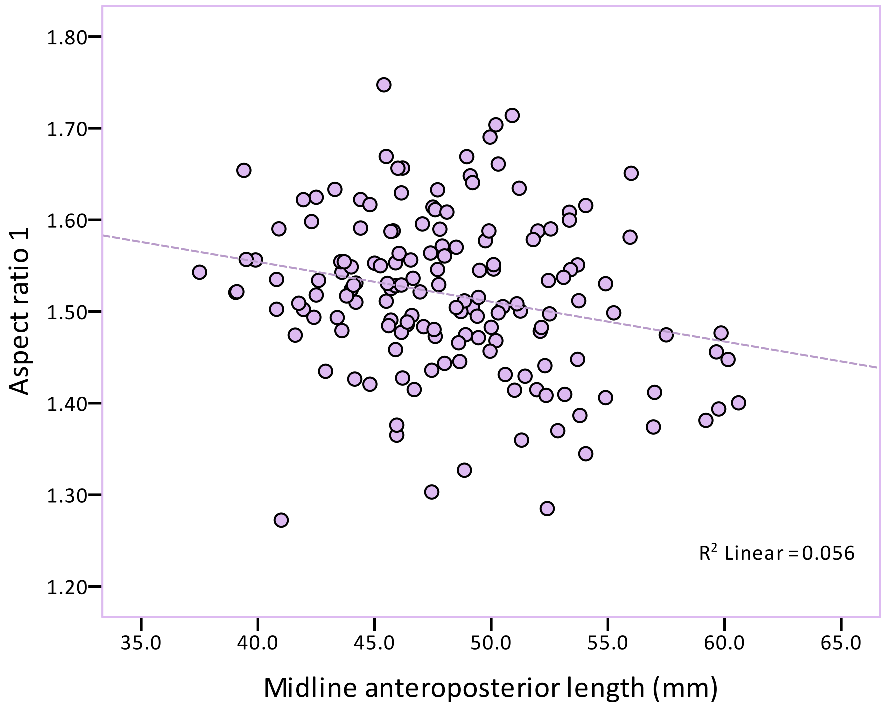

Figure 19: Correlation between MAP and Aspect ratio 1 of tibia (N = 161) showing no correlation. Pearson's r = -0.23.

6.2.4: Correlation between tibial length and other tibial dimensions

The length of the tibia was found to have statistically significant correlation with APMC (*Pearson's r* = 0.59, *p value* 0.00), MAP (*Pearson's r* = 0.66, *p value* 0.00) and ML (*Pearson's r* = 0.68, *p value* 0.00). There was no correlation between length of tibia and Aspect ratio 1 (*p value* 0.64), as shown in Table 10. The length of the tibia can therefore be used as a good predictor of APMC, MAP and ML dimensions of the tibia (*p value* 0.00).

S.No.	X- Axis	Y- Axis	Pearson's r value	p value
1	Length of tibia	APMC	0.59	0.00
2	Length of tibia	MAP	0.66	0.00
3	Length of tibia	ML	0.68	0.00
4	Length of tibia	Aspect ratio 1	-0.06	0.64

APMC- Anteroposterior length of medial condyle; MAP- Midline anteroposterior length; ML- Mediolateral length at transepicondylar axis; AR 1- Aspect ratio 1(ML/APMC)

Table 10: Correlation of Length of tibia with other femoral dimensions

The correlation scatter plots between Length of tibia and other tibial dimensions are shown in Figures **20, 21, 22 and 23**.

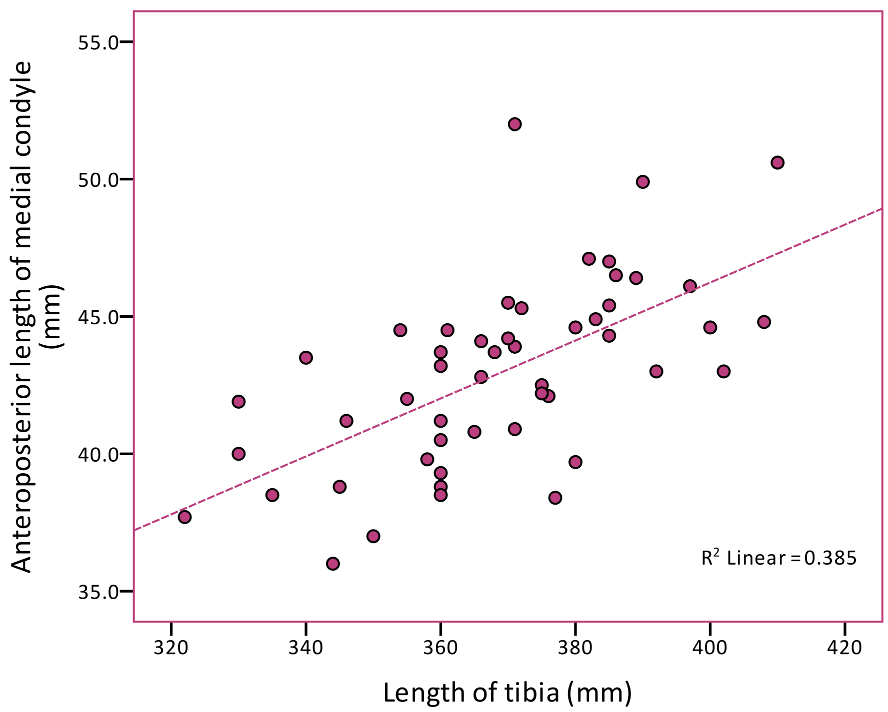

Figure 20: Correlation between Length of tibia and APMC (N = 50), showing moderate correlation. Pearson's r = 0.59

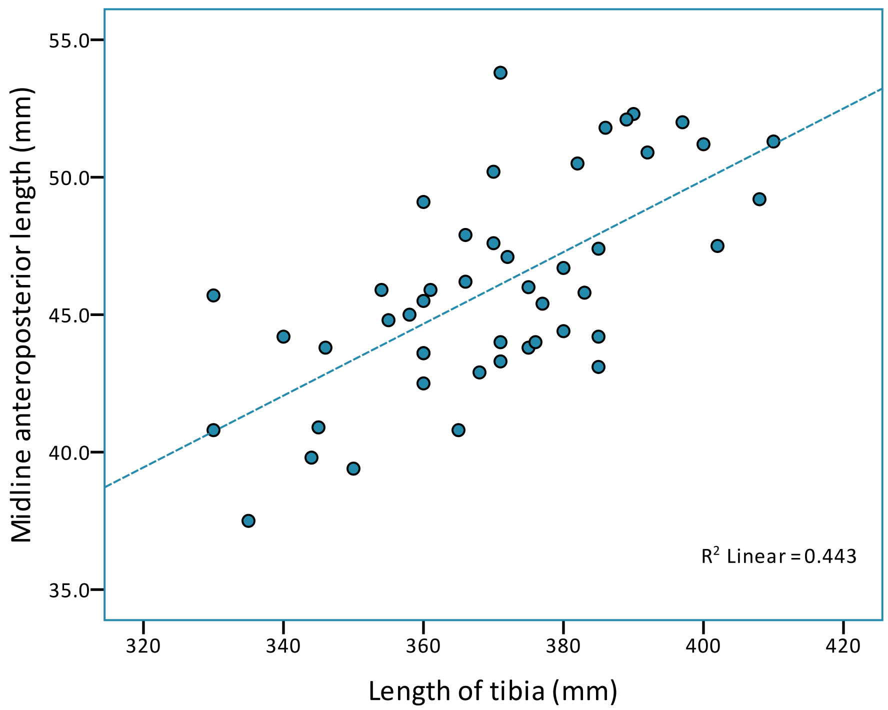

Figure 21: Correlation between Length of tibia and MAP (N = 50), showing positive correlation. Pearson's r = 0.66

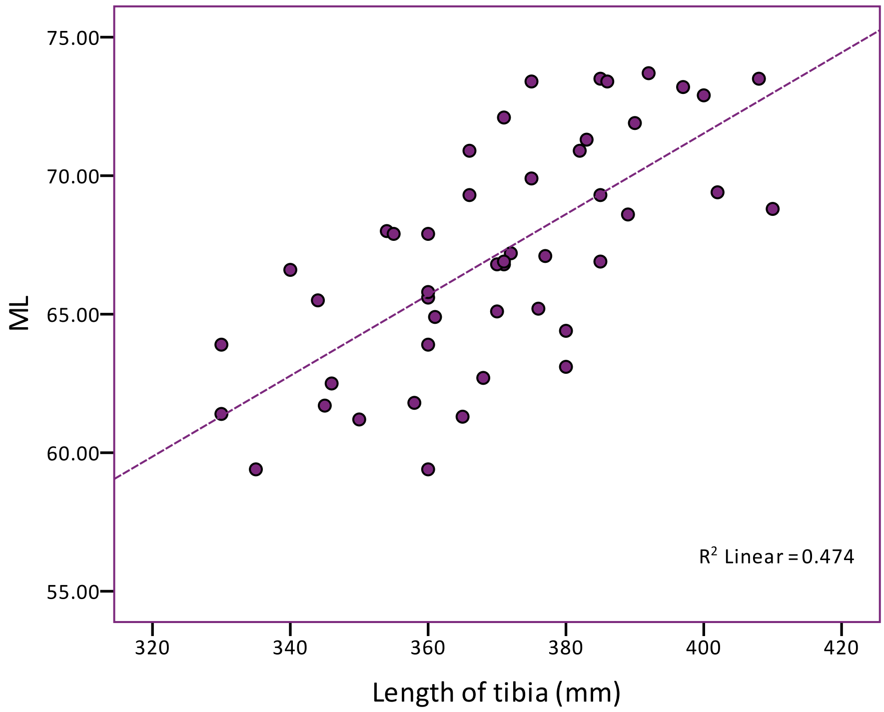

Figure 22: Correlation between Length of tibia and ML (N = 50), showing moderate correlation Pearson's r = 0.68

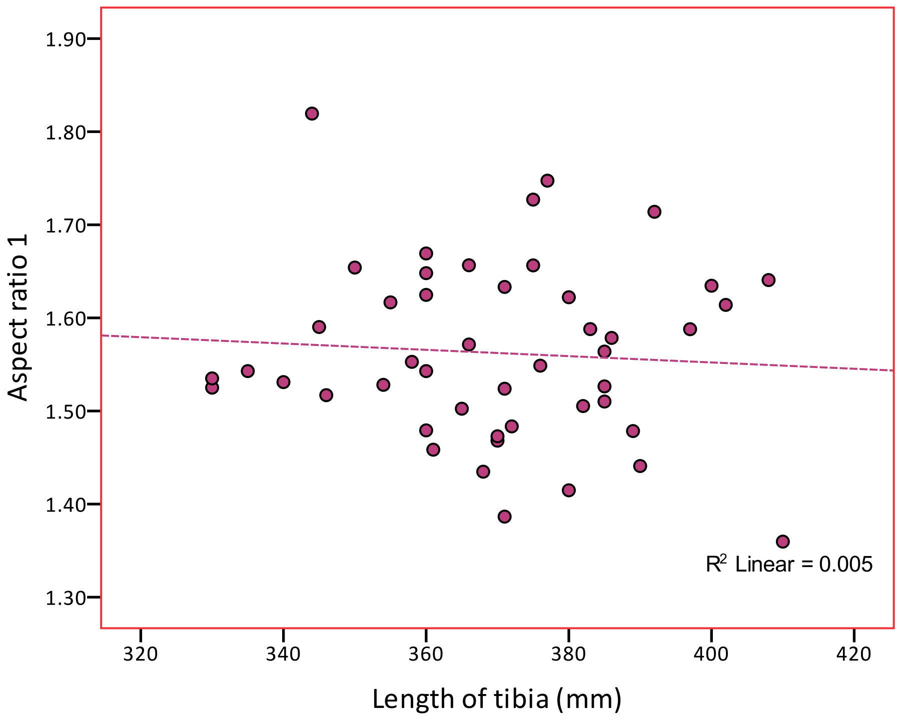

Figure 23: Correlation between Length of tibia and Aspect ratio 1 (N = 50) Pearson's r = -0.06.

6.2.5: Regression analysis in tibia

As shown in Table 9 and 10, there is a good correlation between APMC and ML, MAP and ML, Length of tibia and APMC, Length of tibia and ML. Linear regression analysis was done for the above variables (Table 11) which showed a positive linear correlation, which were independent of each other and were not belonging to a mixed sample (scatter plots Figures 15, 16, 20 and 22).

Independent variable	**Dependent variable**	**Regression equation**
APMC	ML	ML = 26.82 + 0.92 (APMC)
MAP	ML	ML = 30.71 + 0.78 (MAP)
Length of tibia	APMC	APMC = 4.04 + 0.1 (Length)
Length of tibia	ML	ML = 6.37 + 0.16 (Length)

APMC- Anteroposterior length of medial condyle; MAP- Midline anteroposterior length; ML- Maximum mediolateral length

Table 11: Linear regression equations for various tibial dimensions

For example:

I) For given APMC = 50.85 mm; using the regression equation,

$$ML = 26.82 + 0.92\ (50.85)$$

$$ML = 73.60 \text{ mm}$$

II) For given MAP = 48.0 mm; using the regression equation,

$$ML = 30.71 + 0.78\ (48.0)$$

$$ML = 68.15 \text{ mm}$$

6.3: Results of Cadaveric measurements

Dissection of the knee joint was performed on 14 cadavers, of which 8 were female and 6 were male. The distal femur, proximal tibia and patella were exposed after carefully dissecting out the surrounding soft tissue. None of the cadaver knees revealed any evidence of gross pathology, previous surgical procedures or traumatic lesions.

6.3.1: Morphometric measurements of distal femur in cadavers

6.3.1.1: Comparison of right and left dimension

The means of all the measured parameters was compared between the two sides (right and left) using the paired t test for the comparison of means and results are as shown in Table 12. It was found that there was no significant difference between the two sides in any of the morphometric dimensions measured.

This is consistent with the findings in the dry bones measurement given in section 6.1.1. The measurements of both the sides also showed very strong correlation (with Pearson's coefficient 'r' value high and close to 1).

Pair	Dimension	Mean	p value for paired t test	Pearson's r value	Correlation p value
1	RAPMC	59.2	0.24	0.97	0.00
	LAPMC	58.8			
2	RAPLC	59.9	0.45	0.88	0.00
	LAPLC	59.5			
3	RML	75.2	0.90	0.88	0.00
	LML	75.2			
4	RWMC	26.6	0.90	0.51	0.57
	LWMC	26.7			
5	RWLC	28.4	0.97	0.63	0.01
	LWLC	28.5			
6	RHMC	35.1	0.89	0.89	0.00
	LHMC	35.2			
7	RHLC	34.5	0.62	0.81	0.00
	LHLC	34.2			
8	RDIC	25.7	0.16	0.34	0.22
	LDIC	23.7			
9	RWIC	19.3	0.07	0.82	0.00
	LWIC	18.6			

APMC - Anteroposterior length of medial condyle; APLC- Anteroposterior length of lateral condyle ML- Mediolateral length at transepicondylar axis; WMC– Width of medial condyle; WLC- Width of lateral condyle; HMC– Height of medial condyle; HLC- Height of lateral condyle; DIC- Depth of Intercondylar notch; WIC- Width of Intercondylar notch.

Table 12a: Comparison of morphometric data of right and left distal femur in cadaveric specimens.

Pair	Dimension	Mean	p value for paired t test	Pearson's r value	Correlation p value
1	RA	35.5	0.88	0.73	0.00
	LA	35.6			
2	RB	56.1	0.35	0.84	0.00
	LB	55.5			
3	RCM	22.9	0.69	0.81	0.00
	LCM	23.1			
4	RCL	24.6	0.08	0.90	0.00
	LCL	24.1			
5	RX	12.3	0.41	0.62	0.01
	LX	11.7			
6	RY	30.4	0.88	0.86	0.00
	LY	30.3			
7	RLM	113.8	0.47	0.89	0.00
	LLM	114.7			
8	RLL	116.0	0.75	0.91	0.00
	LLL	116.3			

A - First horizontal dimension on anterior articular surface; B - Second horizontal dimension on anterior articular surface; CM - Width of the articular surface of medial condyle along the transepicondylar plane; CL - Width of the articular surface of lateral condyle along the transepicondylar plane X - Patellar extension of articular surface on the lateral condyle; Y - Anteroposterior extent of anterior femoral articular surface; LM - Length of medial condyle; LL – Length of the lateral condyle; AR- Aspect ratio (ML/APMC).

Table 12b: Comparison of morphometric data of right and left distal femur in cadaveric specimens (articular surface measurements).

6.3.1.2: Gender-wise comparison of distal femoral dimension

In prosthesis design of distal femur, in order to closely replicate normal anatomy and functionality the dimensions that play critical role are AP and ML. Therefore in order to assess the need for a gender specific prosthesis one needs to consider the differences in these measurements in the two genders. In this study the APLC and ML measurements were significantly more in males than in females (difference of APLC: 4.1mm , *p value* 0.03 , difference of ML: 4.4mm, *p value* 0.02). The gender differences among other measurements of the distal femur are as seen in Table 13 which were compared by using the independent t test for comparison of means.

Femoral dimension	Gender	Mean (mm)	SD	p value Significance of difference between means
Length	Male	1563.3	121.76	0.41
	Female	1523.1	53.91	
APMC	Male	61.2	5.88	0.11
	Female	57.3	2.68	
APLC	Male	62.0	4.54	0.03
	Female	57.9	1.87	
ML	Male	77.7	4.31	0.02

	Female	73.3	2.08	
WMC	Male	27.0	2.10	0.71
	Female	26.4	2.95	
WLC	Male	29.1	3.05	0.41
	Female	27.9	2.31	
HMC	Male	36.9	4.30	0.12
	Female	33.8	2.54	
HLC	Male	36.4	3.70	0.02
	Female	32.8	1.51	
DIC	Male	25.4	3.94	0.58
	Female	24.3	3.53	
WIC	Male	19.0	2.14	0.94
	Female	18.9	2.27	

APMC - Anteroposterior length of medial condyle; APLC- Anteroposterior length of lateral condyle ML- Mediolateral length at transepicondylar axis; WMC– Width of medial condyle; WLC- Width of lateral condyle; HMC– Height of medial condyle; HLC- Height of lateral condyle; DIC- Depth of Intercondylar notch; WIC- Width of Intercondylar notch.

Table 13: Gender differences between various femoral condylar measurements

6.3.1.3: <u>Correlation between APMC and ML in cadaveric distal femur</u>

As shown in Figure 24, in the cadaveric measurements of distal femur, it was found that there were strong correlations between APMC and ML (Pearson's r = 0.90, *p value* 0.00). The regression analysis done derived an equation (as below) with ML as the dependent and APMC as the independent variable.

$$\boxed{\text{Regression equation: ML} = 30.94 + 0.75(\text{APMC})}$$

This is similar to the findings in the dry bone measurements where the regression equation was: ML = 29.11 + 0.78 (APMC). Therefore, there exists a linear relationship between APMC and ML of distal femurs in Indian population.

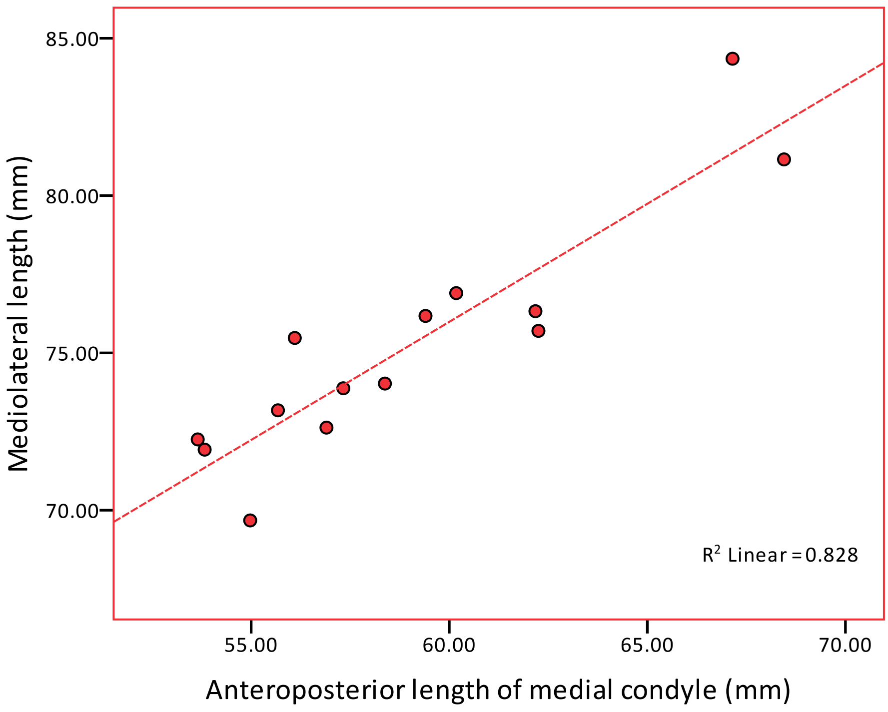

Figure 24: Correlation between APMC and ML of cadaveric distal femur

6.3.1.4: Correlation between various cadaveric femoral dimensions (Gender wise)

As seen in the scatter plot in Figure 25, the female knees included in this study had smaller Mediolateral dimension for given Anteroposterior length of medial condyle.

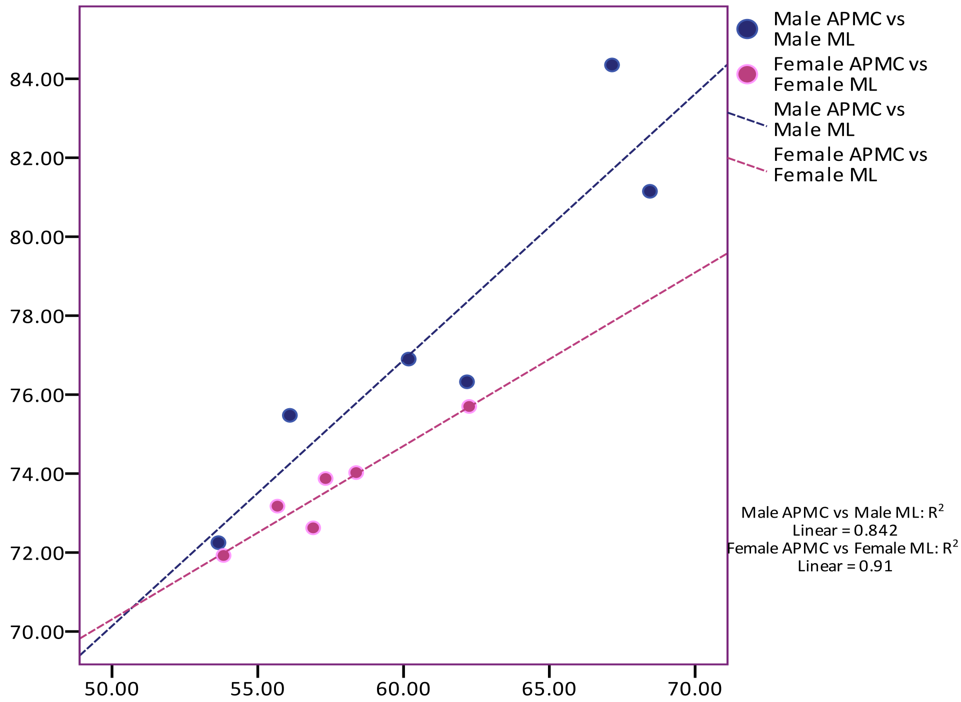

Figure 25: Gender wise correlation between APMC and ML in cadaveric knees, showing positive correlation in both sexes. Pearson's r (male) = 0.91, Pearson's r (female) = 0.95.

On applying linear regression, the following regression equations were obtained for both sexes.

Regression equation in Male knees: ML = 36.44 + 0.67(APMC)

Regression equation in Female knees: ML = 36.53 + 0.63(APMC)

6.3.1.5: Gender wise results of the articular surface measurements of the distal femur

The gender differences among articular surface measurements of the distal femur are seen in Table 14, which were compared using the independent t test for comparison of means. There was a statistically significant difference observed between sexes in the dimensions of: B - Second horizontal dimension on anterior articular surface; Y - Anteroposterior extent of anterior femoral articular surface and LL - Length of medial and lateral condyle.

Femoral dimension	Gender	Mean (mm)	SD	Significance of difference between means p value
A	Male	35.9	2.88	0.67
	Female	35.2	2.87	
B	Male	57.8	4.60	0.07
	Female	54.3	2.07	
CM	Male	23.6	2.05	0.37
	Female	22.5	2.29	
CL	Male	25.2	2.49	0.22
	Female	23.7	1.96	
X	Male	13.2	2.01	0.16
	Female	11.2	2.75	
Y	Male	32.2	2.97	0.04

	Female	29.0	2.39	
LM	Male	119.2	8.62	0.06
	Female	110.5	7.52	
LL	Male	123.1	8.39	0.00
	Female	111.0	4.22	
AR	Male	1.27	0.06	0.77
	Female	1.28	0.03	

A - First horizontal dimension on anterior articular surface; B - Second horizontal dimension on anterior articular surface; CM - Width of the articular surface of medial condyle along the transepicondylar plane; CL - Width of the articular surface of lateral condyle along the transepicondylar plane X - Patellar extension of articular surface on the lateral condyle; Y - Anteroposterior extent of anterior femoral articular surface; LM - Length of medial condyle; LL – Length of the lateral condyle; AR- Aspect ratio (ML/APMC).

Table 14: Gender differences between various femoral articular surface measurements

6.3.2: Morphometric measurements of proximal tibia in cadavers

6.3.2.1: Comparison of right and left tibial dimensions

The means of all the measured parameters of proximal tibia were compared between the two sides (right and left) using the paired t test for the comparison of means and results are as shown in Table 15. It was found that there was no significant difference between the two sides in any of the morphometric dimensions measured in the proximal tibia. This is consistent with the findings in the dry bones measurement given in Table 6, section 6.2.1.

The measurements of both the sides also showed good correlation (with Pearson's coefficient 'r' value high and close to 1).

Pair	Dimension	Mean	p value for paired t test	Pearson's r value	Correlation p value
1	RAPMC	46.5	0.69	0.78	0.00
	LAPMC	46.2			
2	RAPLC	42.3	0.53	0.76	0.00
	LAPLC	42.0			
3	RMAP	44.9	0.55	0.70	0.00
	LMAP	45.3			
4	RML	69.0	0.75	0.93	0.00
	LML	68.8			

APMC - Anteroposterior length of medial condyle; APLC-Anteroposterior length of lateral condyle; MAP – Midline anteroposterior length; ML-Maximum Mediolateral length.

Table 15: Comparison of morphometric data of right and left proximal tibia in cadaveric specimens

6.3.2.2: <u>Gender-wise comparison of proximal tibial dimension</u>

The gender differences among other measurements of the proximal tibia are as seen in Table 16 which were compared by using the independent t test for comparison of means. This showed that there was statistically significant difference in APMC (difference of 3.01 mm; males more than females) and APLC (difference of 2.72 mm; males more than females).

Tibial dimension	**Gender**	**Mean (mm)**	**SD**	**Significance of difference between means p value**
APMC	Male	48.01	2.32	0.08
	Female	45.0	3.19	
APLC	Male	43.62	2.40	0.02
	Female	40.90	1.47	
MAP	Male	45.79	3.90	0.46
	Female	44.56	1.57	
ML	Male	70.7	5.07	0.17
	Female	67.4	3.15	

APMC - Anteroposterior length of medial condyle; APLC- Anteroposterior length of lateral condyle; MAP – Midline anteroposterior length; ML-Maximum Mediolateral length.

Table 16: Gender differences between various tibial condylar measurements

6.3.2.3: <u>Gender wise results of the articular surface measurements of the proximal tibia</u>

On comparison of gender differences between tibial articular surface measurements there was no difference observed (Table 17). Therefore, articular surface measurements of the proximal tibia are not critical in determining the implant size.

Tibial dimension	Gender	Mean (mm)	SD	Significance of difference between means p value
K	Male	30.8	2.34	0.39
	Female	40.7	3.94	
L	Male	30.9	2.64	0.79
	Female	30.7	2.38	
M	Male	37.9	2.45	0.87
	Female	37.8	2.52	
N	Male	44.9	2.74	0.32
	Female	44.4	2.40	

K – Mediolateral dimension of the lateral condylar articular surface; L - Mediolateral dimension of the medial condylar articular surface; M - Anteroposterior dimension of the lateral condylar articular surface; N - Anteroposterior dimension of the medial condylar articular surface

Table 17: Gender differences between various Tibial articular surface measurements

6.3.2.4: Correlation between APMC and midline AP (MAP) with ML in cadaveric proximal tibia

In the cadaveric measurements of proximal tibia, it was found that there were strong correlations between APMC and ML (Pearson's r = 0.67, *p value* 0.00) and between MAP and ML (Pearson's r = 0.76, *p value* 0.00) as shown in figures **26 and 27**.

The **regression analysis** done derived an equation (as below) with ML as the dependent and APMC and MAP as the independent variable.

Regression equation: ML = 25.76 + 0.93(APMC)

Regression equation: ML = 16.11 + 1.17(MAP)

This is similar to the findings in the dry bone measurements where the regression equation was: ML = 26.82 + 0.92 (APMC). Therefore, there exists a linear relationship between APMC and ML of proximal tibias in Indian population.

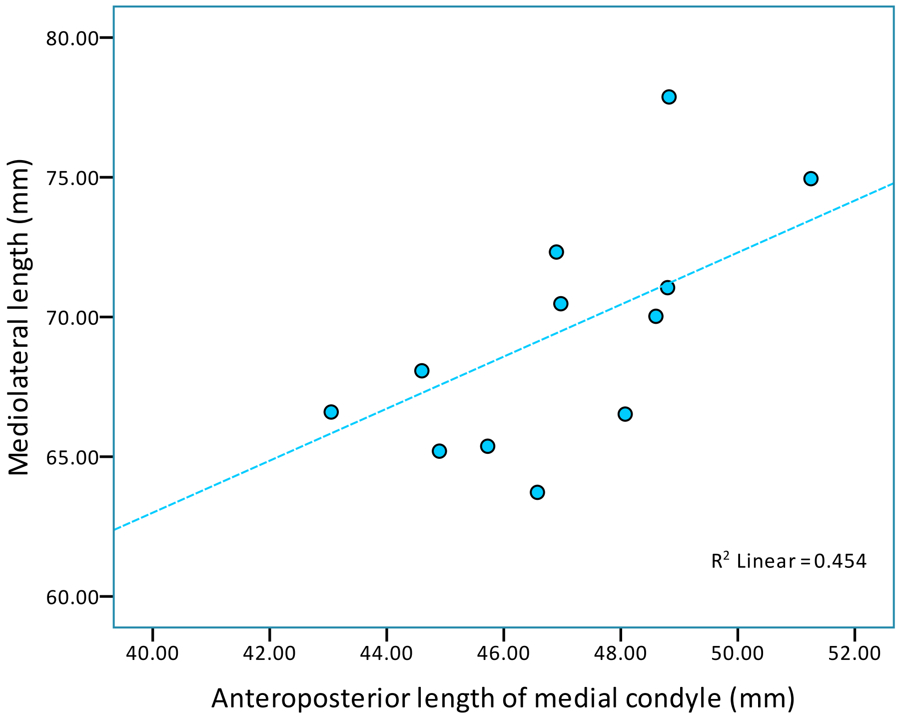

Figure 26: Correlation between APMC and ML of cadaveric proximal tibia, showing positive correlation. Pearson's r = 0.67.

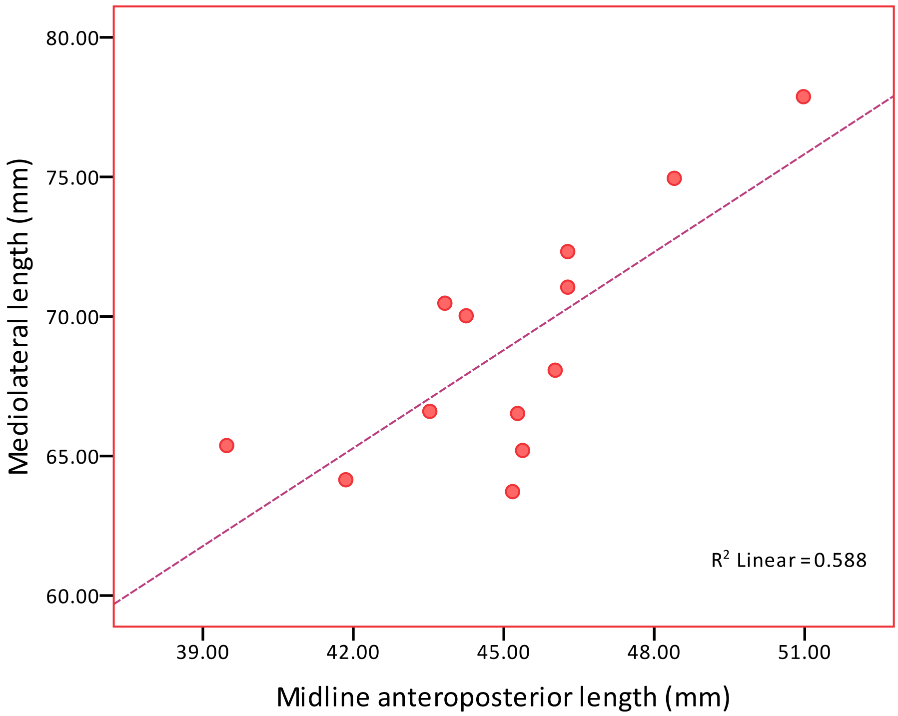

Figure 27: Correlation between MAP and ML of cadaveric proximal tibia, showing positive correlation. Pearson's r = 0.76.

6.3.2.5: Gender-wise correlation between APMC and ML in proximal tibias.

The APMC and ML of the proximal tibia in males showed strong correlation (Pearson's r = 0.82), whereas in females the ML dimension was smaller for a given APMC dimension.

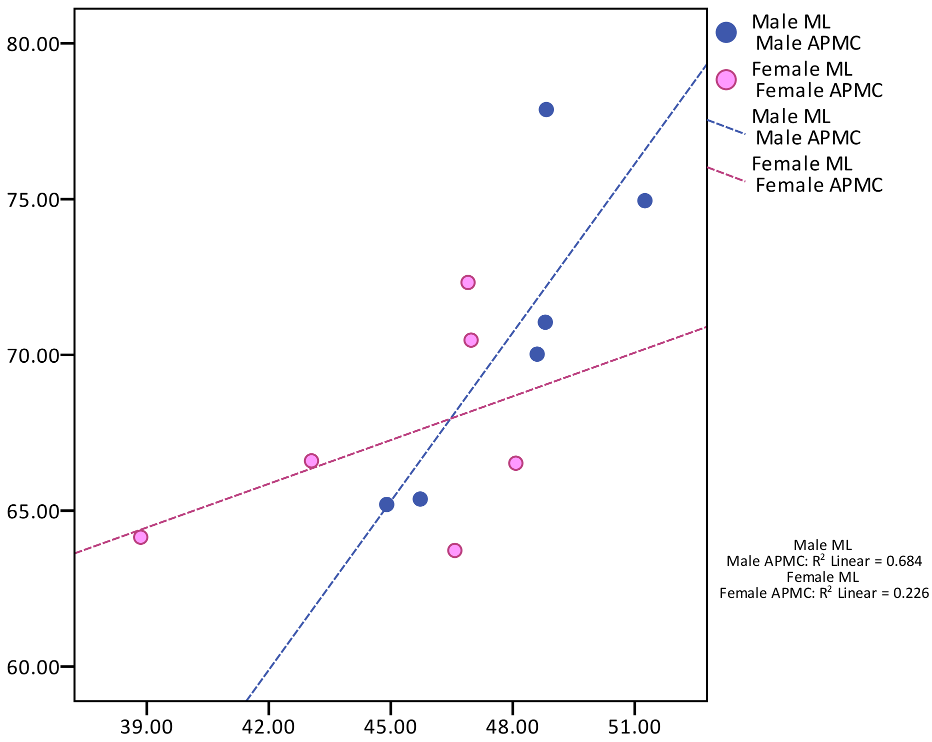

Figure 28: Gender-wise correlation between APMC and ML in proximal tibias, showing positive correlation in both sexes. Pearson's r (male) = 0.82, Pearson's r (female) = 0.47.

Linear regression analysis was done for the APMC and ML variables which showed a positive linear correlation, which were independent of each other and were not belonging to a mixed sample

7. DISCUSSION

This research was aimed to study the morphometry of normal adult knees in the Indian population in order to assess the need for a knee arthroplasty system specific to the Indian population by measuring the various dimensions of the distal femur, proximal tibia and patella in cadavers and dry bones, and comparing the findings with current arthroplasty systems in India and other racial groups around the world.

Morphometric measurements in general have been used in research for; identifying and characterizing structural differences among populations, racial groups and between sexes. In knee arthroplasty related studies, morphometric measurements of the knee joint have been done to describe racial and gender differences and also to understand prosthesis designs.

Knee arthroplasty, is the surgical procedure that replaces the knee joint surfaces, to alleviate the pain and disability caused by osteoarthritis which cannot be managed by conservative treatment(17). Total knee arthroplasty (TKA) is a precision surgery, requiring accurate soft tissue balancing and resection of bone thickness equal to the thickness of the prostheses implanted, so that flexion - extension spacing are equal, allowing joint stability throughout the range of motion(18,19). The success of TKA depends to a large extent on prostheses selection, accurate sizing and proper placement of the components (20,21).

The femoral component

In the sizing of the femoral component, the anteroposterior diameter of medial condyle (APMC) is important in maintaining flexion - extension spacing and optimal tension in the quadriceps mechanism (21), whereas the mediolateral diameter (ML) determines adequate coverage of the resected bone surface, allowing even stress distribution, tension-free wound closure, and smooth tracking of the patellar component in the trochlear groove during flexion (22,23). Accurate sizing of the femoral component is essential in the anteroposterior dimension and the permissible error in component selection should not exceed 3 to 4 mm(22). Oversizing in the anteroposterior dimension alters the balance in flexion-extension spacing, resulting in postoperative flexion tightness because of increased tension in the quadriceps mechanism(21,24).

Comparing the right and left sides of distal femur

In this study, in the comparison of right and left femurs in dry bones it was found that amongst most parameters there was no difference between the dimensions of the two sides except that of

APMC which showed a statistically significant difference between the mean of right (57.56) and left (58.78) side, but this difference of 1.22 mm may not be clinically significant. This difference was not observed in the measurements of the cadavers. Other studies within each racial group also showed no statistical difference between right and left sides for distal end of femur (7–9,16,25,26). This therefore proves the assumption in common practice that, there are no significant differences on anatomical and functional comparison of parameters from one side to the other (although symmetry is unknown) (27).

Comparing gender differences of the distal femur

There has been considerable recent debate, with conflicting suggestions regarding whether distinct TKA components with different sizes and shapes are necessary to accommodate morphologic differences of the distal femur between men and women. Given that women are the recipients of approximately two third of all total knee arthroplasty surgeries performed, if in fact there are gender differences in the shape and dimensions of the distal femur, then a design that accommodates these differences might be appropriate.

On comparing between male and female dimensions of the distal femur in this study (done on 14 cadavers), it was found that the means of all dimensions including APMC (males: 61.28 ± 11.6 mm; females: 57.34 ± 5.36 mm, *p value 0.16*), APLC (males: 62 ± 9.08 mm; females: 57.9 ± 3.74 mm, *p value 0.03*); ML (males: 77.74 ± 8.62 mm; females: 73.39 ± 4.16 mm, *p value 0.02*), were more in males than in females and correspondingly the Aspect Ratio (males: 1.27 ± 0.06 mm; females: 1.28 ± 0.03 mm, *p value 0.77*) females more than males. The analysis does not reveal a statistically significant difference [with p value > 0.05(except in case of APLC and ML)] between the two genders. This could be due to the small sample of cadavers studied.

These are similar to the findings of Vaidya et al. in Indian population showing that the mean AP in men was 61.09 mm and in women was 55.58 mm studied on eighty six knees measured using CT scans (15).

Studies on gender differences of distal femur in other races

Caucasian race:

Studies done in both the American and Canadian populations of the Caucasian race (3,8,24,28–31), found that there was a significant difference in the means of various dimensions of the distal femur between genders. Hitt et al., Clarke et al. and Mahoney et al. found that the aspect ratio in women was greater than in men similar to the present study. Hitt et al. measured the intraoperative anatomy of the distal femur in a cohort of 337 adult male and female patients and then compared these measurements with the geometries of modern total knee prostheses Although it was clear that the systems which were evaluated approximated the mean AP to ML ratios of the entire population, the prosthesis did not as accurately match the subpopulation of female patients, suggesting that anthropometric gender disparities account for femoral component overhang in women and underhang in men with several contemporary implants (8).

Asian races

Studies done in Chinese (9,14,32,33), Japanese(34) , Korean (26,35) and Thai (36) populations showed that the female subgroup have significantly smaller femoral ML dimension than that of male subgroup. Chin et al.(28)studied the anteroposterior (AP) and mediolateral (ML) dimensions of 200 consecutive osteoarthritic knees undergoing unilateral primary TKA and found, on average, the distal femoral APMC was 10.5% more in men than in women and the mean ML dimension was 13.7% wider in men than in women, with an aspect ratio (AP/ML ratio) of 0.82 for women and 0.79 for men (*p value* 0.00) .

In the present study the APMC in the males was 6.3% more than that in females and the ML was 5.6% more in males as compared to females. This difference indicates not only that, men on average have larger distal femora than women but the shapes are different.

The mean APMC of females as measured in this study (57.3 mm) is significantly smaller than that observed in the women of Caucasian (70.7 mm) and Japanese (62.4 mm) races. The findings on comparison studies (33,34,37) stating the difference between Caucasian and Chinese and Japanese population groups found that females have a significantly narrower distal femur than Caucasian females for the same AP dimension. Also there were tendencies to downsize the femoral component in some female patients intra-operatively (while using unisex components) because of difficulties accommodating the ML dimension of the prosthesis that was optimal in the AP dimension. Such results emphasize the fact that anatomical variations in various racial and ethnic groups and sexual dimorphism in humans ensures the need for a gender and probably race specific prostheses for the distal femur.

Comparison of distal femur dimensions in different racial groups:

Comparison with previous Indian studies:

Bagaria VB et al**.** studied the dimensions of distal femur in 25 patients (15 male and 10 female) using MRI scans. They found that the mean AP (lateral condyle) for distal femur was 65.4 ± 5.0 mm and the mean ML was 74.3 ± 5.9 mm (16). According to our study of dry unpaired femurs (N= 177) measured, the means of APLC was 57.58 ± 3.34 mm, ML was 74.96 ± 4.08 mm and Aspect ratio of femur was 1.29 ± 0.05. Though the ML dimension was similar the APLC dimension was significantly different.

Femoral Dimension	**Present study (N = 177)**	**Bagaria VB et al. (N = 50)**
APLC (mm)	57.58	65.4
ML (mm)	74.96	74.3
Aspect Ratio	1.29	1.13

Table 18: Comparison of various femoral dimensions of the present study with previous Indian studies.

Studies done in the Caucasian race

Hitt et al. studied the Caucasian population and found that the means of APMC was 67.5 ± 3.6 mm (range, 62.4-75.3 mm), ML was 86.0 ± 5.6 mm (range, 74.9-100.2 mm) and Aspect ratio of femur 1.28 ± 0.07 (range, 1.12-1.37) (8).

Femoral Dimension	**Present study (N = 177)**	**Hitt et al.**
APMC (mm)	58.15	67.5
ML (mm)	74.96	86.0
Aspect Ratio	1.29	1.28

Table 19: Comparison of various femoral dimensions of the present study with other studies done in Caucasian populations.

Studies done in the Asian races

In the study done by Yue et al. among Chinese population (which was done using CT scans and three dimensional reconstruction) the means of APMC was 65.0 ± 2.8 mm (range, 59.4-70.3 mm), ML was 82.6 ± 3.6 mm (range, 72.6-87.1 mm) and Aspect ratio of femur 1.27 ± 0.03 (range, 1.22-1.33) (13,32).

Urabe et al. studied the Japanese population and found that the means of APMC was 62.4 ± 4.5 mm; ML was 74.3 ± 6.6 mm (38).

A study by Ha et al. in the Korean population found that the mean AP of the lateral condyle was 60.8 mm, mean ML being 68.2 mm and aspect ratio being 1.11. This aspect ratio was greater than the Chinese (1.09) but lesser than that of the Japanese (1.29) (39).

In an MRI study of 200 knees done by Chaichankul et al. in the Thai population, it was found that the mean AP was 45.43 ± 4.5 mm, ML was 64.06 ± 6.31 mm and the aspect ratio was 1.41 ± 0.12 (40) .

Femoral Dimension	**Present study**	**Yue et al. (Chinese)**	**Urabe et al. (Japanese)**	**Ho et al. (Korean)**	**Chaichankul et al. (Thai)**
APMC (mm)	58.15	65	62.4	60.8	45.43
ML (mm)	74.96	82.6	74.3	68.2	64.04
Aspect Ratio	1.29	1.27	1.19	1.11	1.41

Table 20: Comparison of various femoral dimensions of the present study with other studies done in Asain populations.

On comparing the studies mentioned above among various population groups it can be observed that there is an obvious trend towards a smaller sized distal femur in Asian groups as compared to Caucasian population. This has been shown in earlier studies in that Chinese knees were smaller than Caucasian knees (33). The mean AP in the Thai study done by Chaichankul et al. is lesser than the other studies among the Asian population because the dimensions on MRI were taken after stimulated distal femoral bone cut.

The mean value of APMC in the present study appears to be smaller than those of the other Asian subgroups. This could be attributed to the fact that this study was done on dry bones with specific standardized bony landmarks whereas the others were radiological (CT and or/ MRI) with or without three dimensional reconstruction, which could have a soft tissue component also being erroneously measured.

The Tibial Component

In Total knee arthroplasty, the geometry of the tibial component should match the normal anatomy as closely as possible. This would provide for the best stability and load transfer and is important in cemented and cementless applications(41) . For the design of a tibial component with maximal coverage, it is essential to have anthropometric data of the proximal tibia at the condylar level. In the present the dimensions studied in the proximal tibia were: Anteroposterior length of medial condyle (APMC); Anteroposterior length of lateral condyle (APLC); Anteroposterior length at the midline (MAP); Maximum mediolateral length (ML).

In this study, of 166 proximal tibias the mean MAP was 48.10 ± 4.7 mm; ML was 68.4 ± 4.87 mm this was similar to the data from other Indian studies where MAP was 47.8 ± 4.3 mm and ML was 73.3 ± 5.3 mm as done by Bagaria et al. (16) using MRI on 25 patients.

A study done by Uehara et al.(41) who studied 100 tibias in the Japanese population showed that mean MAP was 48.3 ± 5.4 mm and ML was 74.3 ± 6.6 mm. These dimensions are similar to the studies done in Indian population.

In view of the similarity in the dimensions between the present study and the other two studies (Bagaria et al., Uehara et al.) which used radiological means for measurement (MRI and CT respectively) it can be suggested that, unlike the femoral component, the tibial component size can be effectively predicted using radiological means preoperatively.

There is however, paucity of further anthropometric data on proximal tibia in Indian population and from other racial groups.

Comparing right and left sides of proximal tibia

This study showed that there was no statistically significant difference between any of the dimensions while comparing the two sides in both dry bones and cadaveric measurements. Therefore, as seen in the femoral dimensions, it would be safe to assume no difference on anatomical and functional comparison of parameters from one side to the other.

Comparing gender differences of proximal tibia

In this study there showed that there was statistically significant difference in APMC: APMC males was 48.01 mm, females was 45.0 mm (difference of 3.01 mm; males more than females, *p value* 0.08) and APLC: APLC males was 43.62 mm, females was 40.90 mm (difference of 2.72 mm; males more than females). However there was no significant difference between genders in the MAP or the ML dimension. This is different from the study done by Uehara et al. (41) where MAP males was 53.8 ± 6.6 mm and in females was 46.6 ± 3.6 mm (*p value* 0.00), also ML in males was 83.0 ± 6.2 mm and in females was 71.7 ± 4.0 mm.

Methods of calculating Aspect ratio in Tibia

In this study the Aspect ratio of tibia was calculated in three ways. The first method (Aspect ratio 1) was calculated as the ratio of ML and APMC, the second method (Aspect ratio 2) was calculated as the ratio of ML and the midline anteroposterior length (MAP) and the third being the ratio of ML and the average of APMC, APLC and MAP (APAVG). However with the application of the ANOVA test; (analysis of variance) this study shows that there is no statistically significant difference between the means of Aspect Ratio 1, 2 or 3 as shown in Table 8. It is concluded that, if any of the condyles are damaged due to disease or trauma, one can accurately predict (due to strong correlation) the Aspect ratio of the tibial component needed to be replaced using any of the other dimensions.

Correlational and regressional analysis for distal femoral and proximal tibial dimensions:

In this study correlation analysis was done for all 177 femurs between the variables; anteroposterior length of medial condyle (APMC), mediolateral length (ML) and aspect ratio. Between APMC and ML there was a good positive correlation (r= 0.75) suggesting that for every increase in APMC there is a proportionate increase in the ML dimension as per the regression equation: ML = 29.11 + 0.78 (APMC). This was similar to the regression equation obtained for cadaveric data between APMC and ML ($r = 0.90$) ML = 30.94 + 0.75 (APMC).

Such predictability for the ML dimension using the APMC could be useful as a tool for evaluating preoperative sizing of femoral prosthesis size. There was however no correlation of any of the femoral dimensions with the length of the femur suggesting the improbability in predicting the femoral component size with the given length of the femur (which could be obtained radiologically).

In correlation analysis of the proximal tibia in 161 dry bones and in cadavers, there was a strong correlation between APMC and ML ($r = 0.75$ in dry bones and $r = 0.67$ in cadavers) and between MAP and ML ($r = 0.75$ in dry bones and $r = 0.76$ in cadavers). There was also a strong correlation between the length of the tibia as measured in dry bones with ML dimensions of the tibia and a moderate correlation with APMC. Therefore, it can be suggested that, unlike femur, tibial length can be a good predictor of the tibial component size as shown in the following regression equation.

ML = 6.37 + 0.16 (Length of tibia).

Articular surface measurements

The articular surface measurements of distal femur and proximal tibia do not find place in scientific literature. However, in view of the authors they are important in understanding and designing prostheses to attain normal anatomical congruity of the implants.

Correlation with other arthroplasty systems in India

Arthroplasty systems use prostheses where, for a given AP the ML is fixed and such a pair would belong to a 'size', said to be standardized by the company. A particular size would be decided for the patient undergoing knee arthroplasty rarely in a preoperative situation and more commonly intraoperatively using various sizing templates. To prevent post op morbidity the 'best fit' for the patient should be in both the dimensions.

Correlation analysis for the distal femoral component and the proximal tibial component was done (Figure **29, 30**) between this study and the values of two prosthetic systems currently used regularly in the Department of Orthopedics, Christian Medical College at Vellore. They are **DePuy** (Johnson and Johnson company; P.F.C. ® Sigma RP System) and **Altius ™ Buechel-Pappas system**.

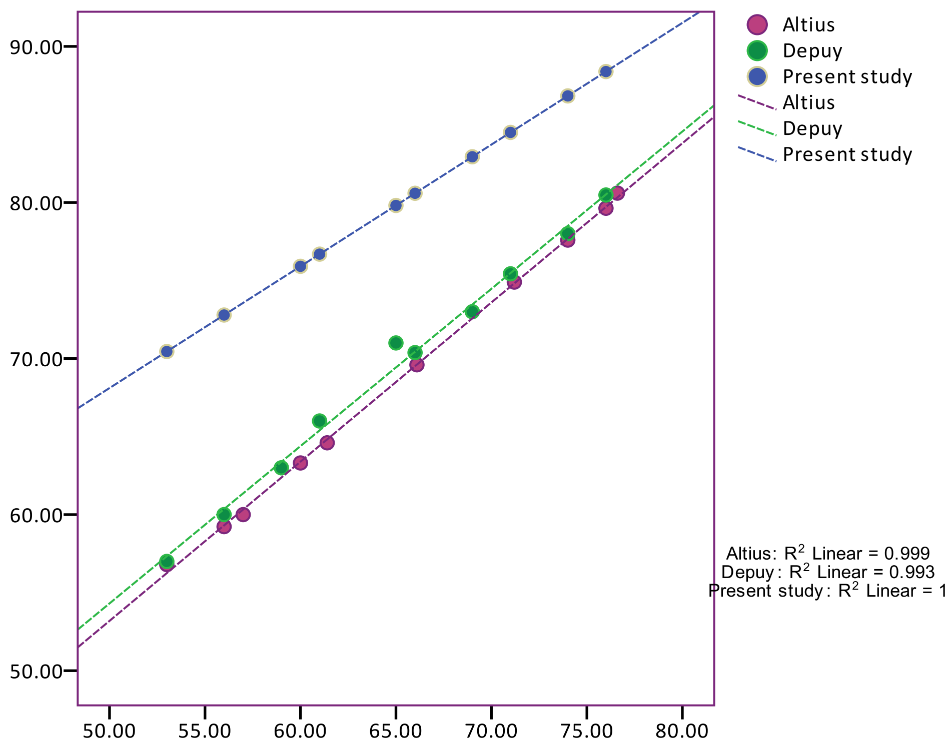

Figure 29: Correlation between APMC and ML of the distal femur in the prosthetic systems as compared to the present study.

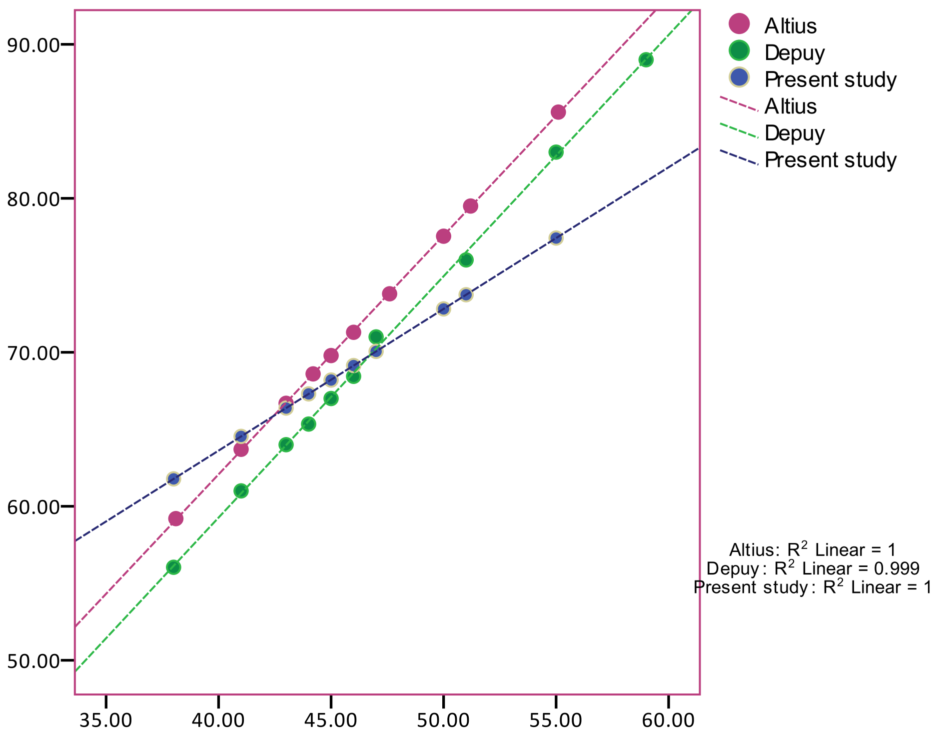

Figure 30: Correlation between APMC and ML of the proximal tibia in the prosthetic systems as compared to the present study.

Analysis showed that the prosthetic systems in use in this institution for the femoral component do not correspond to the measurements of this study. In the prosthetic system currently being used, for a given APMC the ML was significantly narrow as compared to the morphometric measurements of distal femur, whereas the tibial component correlated well with the prosthetic systems.

This finding justifies the need for a relook into the prosthetic systems being used in India and the need to design prostheses that would suit the ‘Indian knee’.

8. CONCLUSIONS

- The morphometric measurements of the distal femur and proximal tibia were done in the Indian population by collecting data from adult dry bones and cadaveric knees.

1. In the dry bones the mean APMC, ML and Aspect ratio for the distal femur were 58.15 ± 7.28 mm, 74.96 ± 8.16 mm and 1.29 ± 0.1 respectively. The mean APMC, ML and Aspect ratio for the proximal tibia were 45.12 ± 8.1 mm, 68.4 ± 9.68 mm and 1.52 ± 0.18 respectively.
2. In the cadaveric data the mean APMC, ML and Aspect ratio for the distal femur were 59.25 ± 4.2 mm, 75.5 ± 3.2 mm and 1.27 ± 0.4 respectively. The mean APMC, ML and Aspect ratio for the proximal tibia were 46.5 ± 5.5 mm, 69.05 ± 4.1 mm and 1.48 ± 0.2 respectively.

- On comparing the morphometry of the distal femur between the two genders it was found that the APLC and ML measurements were significantly more in males than in females (difference of APLC: 4.1mm , *p value* 0.03 , difference of ML: 4.4mm, *p value* 0.02). In the morphometry of the proximal tibia it was found that the APMC and APLC measurements were significantly more in males than in females (difference of APMC: 3.01 mm; *p value* 0.08 and difference of APLC: 2.72 mm; *p value* 0.02).

- The aspect ratios of the distal femur and proximal tibia which were calculated by different methods were found to have strong correlation with each other suggesting alternative methods of measuring the Aspect ratio in case of damage or disease.

- On comparing with other racial groups the dimensions of the distal femur were smaller as compared to the Caucasian and other Asian races. No such differences were found while comparing the dimensions of the proximal tibia.

- The femoral component of the present knee arthroplasty systems that were considered in this study significantly differed from the distal femoral dimensions obtained whereas the tibial component correlated well with the bone dimensions obtained in this study.

Hence it can be suggested that there is a need for redesign of the present knee arthroplasty systems incorporating the different dimensions of the distal femur and the gender differences as measured in the Indian population in this study.

9. LIMITATIONS

- Limitations in sample size:

This study has a relatively small sample size among the cadavers studied. This study included data from 14 cadavers and each group of male or female having no more than 7, 8 cadavers respectively. If a larger sample size was studied, other significant differences may also be noticed. However, the magnitude of the difference likely remains small.

- Limitations in analysis:

Another limitation of the present study is that some cases are still at a considerable distance from the line of best fit, and thus are significant outliers in the correlation analysis. Nevertheless, the vast majority of cases (in bone data) in this series of knees seemed to be distributed around the line of best fit, and so we believe that these results provide representative and reliable anthropometric data for the determination of the dimensions of Total knee arthroplasty systems in the future.

10. REFERENCES

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11. ANNEXURES

1. Proforma Data Sheet – 1: Cadaver
2. Proforma Data Sheet – 2: Bone Femur
3. Proforma Data Sheet – 3: Bone tibia
4. IRB clearance letter from the institution
5. Plagiarism screen shot

Annexure I

C

Morphometric Analysis of the Adult human knee

PROFORMA DATA FORM- Cadaver

1. Study ID number:
2. Age if known:
3. Sex:
4. Height:

Measurements of femur	**RIGHT**		**LEFT**	
AP length at Medial condyle				
AP length at Lateral condyle				
ML length at the epicondyles				
Width of medial condyle				
Width of lateral condyle				
Height of medial condyle				
Height of lateral condyle				
Depth of inter-condylar notch				
Width of inter-condylar notch				

Femoral articular surface	**RIGHT**		**LEFT**	
A				
B				
CM				
CL				
LM				
LL				
X				

Y				

Measurements of tibia	**RIGHT**		**LEFT**	
AP length at Medial condyle				
AP length at Lateral condyle				
Midline AP				
Maximum ML length				
Aspect Ratio				

Tibial articular surface	**RIGHT**		**LEFT**	
K				
L				
M				
N				

Measurements of patella	**RIGHT**	**LEFT**
Max Mediolateral width		
Articular Mediolateral width		
Max Superoinferior width		
Articular Superoinferior width		
Maximum Thickness		

Annexure II

B

Morphometric Analysis of the Adult human knee

PROFORMA DATA FORM- Femur

1. Study ID number:
2. Side:
3. Length:

Measurements	(mm)	(mm)
AP length at Medial condyle		
AP length at Lateral condyle		
ML length at the epicondyles		
Width of medial condyle		
Width of lateral condyle		
Height of medial condyle		
Height of lateral condyle		
Depth of inter-condylar notch		
Width of inter-condylar notch		

Femoral articular surface	(mm)	(mm)
A		
B		
CM		
CL		
LM		
LL		
X		
Y		

Annexure III

Morphometric Analysis of the Adult human knee **B**

PROFORMA DATA FORM- Tibia

1. Study ID number:
2. Side:
3. Length:

Measurements of tibia	(mm)	(mm)
AP length at Medial condyle		
AP length at Lateral condyle		
Midline AP		
Maximum ML length		

Tibial articular surface	(mm)	(mm)
K		
L		
M		
N		

Annexure IV

IRB clearance letter

Annexure V

Plagiarism screen shot